

Modeling and Simulation for Mission Operations Work System Design

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ABSTRACT

Work system analysis and design is complex and non-deterministic. In this paper we describe Brahms, a multiagent modeling and simulation environment for designing complex interactions in human-machine systems. Brahms was originally conceived as a business process design tool that simulates work practices, including social systems of work. We describe our modeling and simulation method for mission operations work systems design, based on a research case study in which we used Brahms to design mission operations for a proposed discovery mission to the Moon. We then describe the results of an actual method application project—the Brahms Mars Exploration Rover. Space mission operations are similar to operations of traditional organizations; we show that the application of Brahms for space mission operations design is relevant and transferable to other types of business processes in organizations.

Keywords: business process modeling, multiagent simulation, agent language, work practice, mission operations design.

Introduction

Work systems involve people, machines, tools, documents, and facilities interacting in activities over time. These activities produce goods, services or—as is the case in the work system described in this paper—scientific data. Many work systems we

encounter everyday have existed over a long period of time. Improvement of such work systems is often done through business process analysis and reengineering [7, 8, 13]. But managers must also design work systems de novo.

One of the challenges of work system design is that work systems are often large and complex and persist over a long period of time. This makes the design process complex and non-deterministic. In this paper we describe Brahms, a multiagent modeling and simulation environment for designing complex interactions in human-machine systems.

Brahms was originally conceived of as a business process modeling and simulation tool that incorporates the *social systems of work*, by illuminating how formal process flow descriptions relate to people's actual located activities in the workplace. Our research started in the early nineties as a reaction to experiences with work process modeling and simulation in the T1-order process redesign project at the NYNEX corporation [20]. Although an effective tool for convincing management of the potential cost-savings of the newly designed T1-order process, the modeling and simulation environment NYNEX used (Sparks™ from Coopers & Lybrand) was only able to describe work as a normative workflow. However, the social systems, uncovered in work practices studied by the T1 design team, played a significant role in how work actually got done in NYNEX organizations. Multi-tasking, informal assistance and circumstantial work interactions could not easily be represented in a tool with a strict workflow modeling structure. In response, we began to develop a tool that would have the benefits of work process modeling and simulation, but be distinctively able to represent the relations of people, locations, systems, artifacts, communication and information content

[5]. In Brahms, we model work processes at the work practice level. We describe our modeling and simulation method for mission operations work system design, based on a research case study in which we used Brahms to design mission operations for a proposed discovery mission to the Moon—the Victoria Mission. We then describe the results of an actual method application project; the Brahms Mars Exploration Rover (MER) model of the design of the mission operations work system of the MER robotic mission to Mars scheduled to be launched in 2003 [6, 11].

Mission operations systems for space missions (robot and human) are comprised of a complex network of human organizations, information and deep-space network systems and spacecraft hardware. From the point of view of the MIS community, one of the problems in mission operations design is how mission information systems are related to work practices. From this perspective, space mission operations are similar to the operations of organizations that traditionally are the domain of MIS research. The application of Brahms for space mission operations design is relevant and, as we discuss in the conclusions section, transferable to other types of business processes.

Work Practice

The concept of work practice originates in the research disciplines of socio-technical systems, business anthropology, and management science. Work systems design, as presented here, has its roots in the design of socio-technical systems. This method was developed in the 1950s by Eric Trist and Fred Emery [10, 19] to understand and leverage the advantages of the social and technical aspects of work. Work systems design extends this tradition, focusing on both the informal and formal features of work and applying ethnography and participant observation [3, 9, 12, 25] [29, chapter 16].

Work practice is defined as the collective activities of a group of people who collaborate and communicate, while performing these activities synchronously or asynchronously. Very often, people view work merely as the process of transforming input to output, which is a Tayloristic view. Sometimes, for example when processing a customer order, the input and output of the work is necessarily well defined. But often it is more difficult to describe human interaction. Consider a group of scientists on a discovery mission. Exploration involves physical search of a landscape, pursuing broad scientific questions, not processing or searching for preformulated data, as in office work. To describe scientific work, we must consider how instruments (often remotely controlled) create data sets, and how distributed teams collaboratively construct meaningful information.

Work practice includes how people behave in specific situations, at specific moments in the real world. To describe people's circumstantial behavior we need to include ecological (environmental) influences on individual activity (not only problem-solving behavior), such as collaboration, "off-task" behaviors, multi-tasking, interrupted and resumed activities, informal interaction, use of tools, and movements [5, 23].

Brahms is a modeling and simulation environment for representing work practice using a multiagent rule-based activity language; models are simulated using the Brahms engine. This paper discusses how we are using Brahms to *design* the work system for mission operations of robotic space missions to the Moon and Mars. The attentive reader might question how we can *design* a work practice? Indeed, a work practice is not designed, but it emerges over time. The question is; can a model at the work practice level be useful for the design of mission operations? We hypothesize that the detailed,

holistic representation of work will be especially useful for revealing problems of workflow and timing that a more abstract representation of work would take for granted [1, 2, 5, 24].

Brahms Language

Brahms has a multiagent language for describing agents and/or objects performing activities. We will briefly explain the modeling concepts of the language. For a more detailed description of the language see Sierhuis [23] and van Hoof & Sierhuis [27]. Brahms models are not necessarily as detailed as models of cognitive problem solving (though a modeler could choose to do this), nor are they as general as functional models of business processes (see Figure 1).

[FIGURE 1 HERE]

Brahms models describe a work process at the work practice level. The language embodies assumptions about how to describe social situations, workplaces and work practice.

Agents and Groups

Agents can represent individuals, a group of individuals or model-based systems, such as “software agents.” Agents can belong to multiple groups (multiple group inheritance), such that individual behaviors are blends of different norms, belief systems, roles, etc.

For example, in the domain of missions operations we can represent the science operations team as a single Brahms agent with the team’s behavior represented by the agent’s “individual” behavior. The science operation team is actually part of a larger group called the science team. We can represent the science team as a Brahms group with

more “general” behavior. By specifying that the science operations team agent is a member of the science team group, the agent will have a combined behavioral spectrum of its individual behavior plus the inherited more general science team behavior. The definition of agents and groups is completely under control of the modeler and thus the level at which we model agents is model-specific. We could easily represent agent “Joe” and “Joanne” as individual agents and members of the science operations team group, which in turn could be represented as a Brahms group. In such a model we represent individual team members, which require more detail.

Objects and Classes

Objects are representations of artifacts in the world or data objects created by information processing, etc. Unlike agents, objects do not behave based on their representations of the world (beliefs), but instead are directly affected by the actual world state (see Beliefs and Facts section). Objects can be generalized into class-hierarchies.

For example, staying with the mission operations domain we can represent the actual information flow of the ground-based work process by modeling the mission operation software systems, as well as the client-computers that the science teams use for accessing these systems. Brahms allows modeling of object-behavior in a similar way as modeling agent-behavior (see Activities section). Using objects we can model information processing behavior of software systems, as well as the human-machine interaction between (human) agents (e.g. the science teams) and the client-computers through which they are accessing the software. In general, intelligent agents that act based on their mental state are represented as Brahms agents, while purely reactive systems and data objects are most often represented as Brahms objects.

Beliefs and Facts

Brahms agents and objects represent the world state internally as propositions called beliefs [14, 18]. For example, agent John believes that his car is the color green. Perhaps Mary believes that John's car is blue. Facts are actual world states, and are global in the simulation world. For example, perhaps the world fact states that John's car is white.

Agent and object beliefs and world facts are the ingredients of a Brahms model that make agents and objects behave over time, when the model is executed in a simulation run. During a simulation every agent and object has a belief set that can be changed by different events: communication, fact detection, reasoning, and activity performance. Similar to Belief-Desire-Intention (BDI) agent architectures, beliefs can represent an agent's beliefs about the world, desires, intentions and goals. Updates in an agent's belief set are evaluated by the agent's reasoning and work-selection engine and affect an agent's reasoning state and actions [30]. Object beliefs, on the other hand, are not representing a mental state of objects, but rather are a representation of data and/or information processing state. Updates in an object's belief set are evaluated by the object's reasoning engine, representing an object's information processing capability. Facts are global to the simulated world, though as in the real world they are only perceivable locally. As shown in Figure 2, in Brahms there is a separation between the belief set of an individual agent or object and the fact set of the world being simulated (i.e. the world state).

[FIGURE 2 HERE]

The purpose is to give the modeler the ability to include each agent/object's "interpretation" of the state of the world. Brahms agents interpret facts in the world by a

situated fact-detection mechanism (i.e. “detectables”), through which agents can internalize world facts as beliefs. Consequently, these new beliefs allow an agent to act (i.e. perform activities; see Activities section). Comparatively, objects are reactive because their actions are based directly on world facts.

For a more complete description of how the complex agent/object’s reasoning engine works see chapter 4 in [23].

Activities

Every agent or object behavior is represented as an activity. A problem-solving task is a kind of activity, but there are many other activities of different character. For example, reading e-mail, answering the phone, having lunch, browsing on the web are activities, but not usually defined as functions (tasks) and may or may not pose problems during a person’s performance [4]. An agent’s situation-dependent behavior is therefore modeled using activities.

Brahms has an activity-based subsumption architecture by which an agent’s activities can be decomposed into subactivities (see Figure 3). An agent engaged in a low-level activity is still performing the “higher level” activities on the activation path of the activity tree (e.g., answering the telephone during a meeting). Activities can be interrupted and resumed, just as humans can multi-task by switching between different activities. Activities always take time, even a “do nothing” activity. An example of a long-term composite activity, from the Victoria model, is searching for water ice in a permanently dark crater. While in this activity, a subactivity is drilling in the lunar surface. A parent activity above the long-term activity is being on a science mission on the South Pole of the Moon.

Activities are modeler-defined elements. Indeed, a Brahms model is the Brahms modeler's interpretation of people's activities in practice (hence the notion of modeling work practice). The Brahms language allows for user-defined primitive and composite activities describing an agent's behavior. There are a number of pre-defined primitive activity types with pre-defined semantics, such as communicate, move, create-object/agent/area, and get and put. Activities may also be written in the Java programming language.

Primitive activities take time, which may be specified by the modeler as a definite quantity or a random quantity within a range. Activity duration can also be parameterized with an agent's belief (e.g. the agent believes a particular meeting will take an hour, which is passed as a parameter at the start of the meeting activity). However, because workframes (see Workframes section) can be interrupted and never resumed, when an activity will finish cannot be predicted from its start time. Primitive activities are atomic behaviors that are not decomposed. Whether something is modeled as a primitive activity is a decision made by the modeler. A primitive activity also has a priority that is used for determining the priority of workframes. An example of a primitive activity in Brahms source code is¹:

```
primitive-activity work-on(Order order) {  
    display: "Working on an order";  \\ a display name  
    priority: 10;  \\ a relative priority
```

¹ The Brahms modeler does not have to write Brahms source code. The Brahms Interactive Development Environment, developed in Java, provides a graphical interface for model development, Brahms source code generation, editing and compilation.

```

    random: true;  \\ the duration is between min and max duration
    min_duration: 3600  \\ in seconds
    max_duration: 10800  \\ in seconds
    resources: order, OrderSystem;  \\ resource objects needed
}

```

This activity specifies an agent working on a specific order (given by the parameter *order*) between one and three hours. It also specifies that besides needing the order to work on the agent also needs to use the order system as a resource. If we were interested in more detail about how the agent performs this activity, we could easily decompose the activity into a composite activity describing how the agent actually works on the order.

For a more detailed description of primitive and composite activities and how they are executed see chapter 4 in [23].

Workframes

An agent cannot always carry out all activities that are possible, given the agent's cognitive state and location. Each activity is therefore associated with a conditional statement or constraint, representing a condition/activity pair, most of the time referred to as a rule [22] [30] [17]. If the conditions of a rule are believed by the agent then the associated activities are performed. In Brahms, such rules are called *workframes*. Workframes are situation-action rules derived from production rules, but because they execute activities, they take time. A workframe precondition tests a belief held by the agent. An example of a workframe for an agent working on customer orders is:

```

workframe Do-Work {
    variables:
        foreach(Order) order;
    when (knownval(order is-assigned-to current))
    do {
        work-on(order);
    }
}

```

If three orders are assigned to the agent (“current”), and the agent has beliefs for three of the orders matching the precondition, Brahms creates three workframe instantiations (wfi) of the workframe Do-Work for the agent, and in each wfi the foreach variable is bound to one of the three orders and the work-on activity is executed once for each order. This means that the agent works on all three the orders, one order at a time. The order in which the agent works on the three orders is indeterminate. Besides the foreach-type variable, the Brahms language includes collectall and forone, respectively allowing the agent to work on all three orders at once or on just one (which one is indeterminate).

A composite activity expresses an activity that may require several activities and workframes to be accomplished. Since activities are called within the do-part (i.e. the body) of a workframe, each is performed at a certain time within the workframe. The body of a workframe has a top-down, left-to-right execution sequence. Preference or relative priority of workframes can be modeled by grouping them into ordered composite activities. The workframes within a composite activity, however, can be performed in any order depending on when their preconditions are satisfied. In this way, workframes can explicitly control executions of composite activities, and execution of workframes

depends not on their order, but on the satisfiability of their preconditions and the priorities of their activities (see Figure 3).

[FIGURE 3 HERE]

For a more detailed description of workframes and how they are executed see [23].

Geography

Where people and things are located affects group performance. For example, the design of the MER mission operation building at JPL affects how long it takes from people to move from their individual offices to the conference room on the second floor, where most of the important meetings are held. Time to move to another area is but one of the factors that influences how things get done. Other location-dependent factors include co-location or distribution of people and artifacts, and use of communication tools,

Indeed, the fact that we cannot ignore the influence of location in our real world activities is one of the reasons conventional workflow models do not represent work practice. The geography model in Brahms represents where activities occur; hence we speak of located behaviors. Agents and objects are located in areas and can move from area to area by performing a move activity. Agents and objects can also carry other agents and objects using the get- and put activities.

The Brahms language allows for the representation of types of user-defined locations (called area definitions), such as buildings, rooms, and offices, but also locations on planets such as craters. Area definitions can be represented hierarchically in a inheritance (is-a) hierarchy. Areas are specific location instances of area definitions. We

can represent a complex hierarchical geography by making areas be part of other areas (using the part-of relationship). Thus we can represent a building with floors and rooms using the part-of relation between the areas. For example, the Floor-1 area can be part of Building-1 area, and Room-1 area can be part of Floor-1. Then, when an agent is located in Room-1 the agent is also located in Floor-1, as well as in Building-1.

Communications

Communication is a special type of activity. When an agent or object communicates, it either sends or receives beliefs from other agents or objects. In Brahms, we are specifically interested in what triggers an activity; often it is a communication. We also model the communication tools as located objects (e.g., telephones, pagers), which are part of a work practice. For example, in both the Victoria and the MER model we model the communication delays to the Moon and Mars respectively, as well as the computer systems used to access and add data to the critical mission operations systems. Human to human communication is modeled as co-located face-to-face communication (which means that the agents have to be in the same location to communicate), phone conversations or e-mail.

Next, we present the Victoria model and simulation outcome.

Mission Operations Work System Design

The work involved in robotic space missions is distributed over a number of human teams and one or more robots. During a mission, teams of scientists, spacecraft engineers, computer scientists and roboticists work together twenty-four hours per day in a dedicated work environment. The team of scientists, headed by the principal investigator (PI), is responsible for deciding what science activity the robot needs to

perform. Based on the science objectives for a next command cycle, teams of engineers decide on the actual command sequence to be “uplinked” to the robot. After the robot receives the uploaded command sequences it executes the commands. At this time the ground-based teams are monitoring the health and returned science data from the robot. Different teams of engineers transform the “downlink” science data into human-readable form. This can be in the form of three-dimensional surface images taken by stereographic cameras, or particular scientific instrument readings from the science “payload” onboard the robot. After the returned science data has been converted and the health of the robot confirmed, the science team performs the next cycle of science decision-making, based on the downlink data. Thus, the uplink cycle starts over again.

The science team is a *user* of the rover, from the perspective that the rover is on the planetary surface being controlled by the Earth-based science team. But by virtue of being people’s arms and eyes on the surface, and by having “autonomous” capability to carry out commands, the rover is more of an *assistant* than a simple tool. In particular, the work can be viewed as distributed between people and robot, and we can ask: who is doing what, where, when, and how?

The Victoria Lunar Mission

Victoria is the name of a proposed long-term semi-autonomous robotic mission to the South Pole region of the Moon. The primary mission objective of Victoria is to verify the presence of water ice and other volatiles within permanently shadowed regions on the Moon. This will be accomplished by gathering the necessary lunar data for analyzing the history of water and other volatiles on the Moon, and by implication in the inner solar system. The Victoria team has decided to use a high-speed semi-autonomous rover.

One of the dominating constraints in any robotic mission is power consumption. In every activity the rover uses energy, therefore the sequence of activities for the rover is constrained by the amount of power available to complete the sequence. When the robot's batteries are low, it needs to return to a sun-exposed spot to recharge its batteries. During the Victoria mission the rover will traverse into permanently dark regions on the Moon. During these traverses the rover will use its neutron detector instrument to detect hydrogen and the Sample Acquisition and Transfer Mechanism (SATM) to drill into the lunar surface and take surface samples to be investigated using an array of science instruments.

A basic work system design problem is to configure the mission operations so the robot's activities inside the permanent dark region are most efficient (i.e. consume the least amount of energy, in order to spend as much time collecting science data).

[FIGURE 4 HERE]

Victoria Mission Operations Work System

Figure 4 represents the work system elements and their relative location during the Victoria mission. The Science Team consists of co-located sub-teams: the Science Operations Team (SOT), the Instrument Synergy Team (IST), and the Data Analysis and Interpretation Team (DAIT). There are two other supporting teams: The Data and Downlink Team (DDT) and the Vehicle and Spacecraft Operations Team (VSOT). The teams communicate with the Victoria rover on the lunar surface using the Universal Space Network (USN), directly and via a lunar orbiter. The flow of data from the rover will be dominated by contextual data and science data. This data will come to NASA/Ames via the Universal Space Network (USN) data connection and will be

automatically converted in near real-time to accessible data formats that can be made available to the teams via data access and visualization applications.

Based on previous experience, the mission designers hypothesized that many issues will affect the decision cycle of the science team, one of which is data overload [26]. They therefore specifically addressed the following questions in the work system design for Victoria:

1. How will science data be gathered collaboratively with the Earth-based science team, rover teleoperator, and the rover on the lunar surface?
2. How will science data be made available to the science team?
3. What is the effect of a particular work system design on the power consumption of the rover during a science traverse into a permanent dark crater?

To answer these questions we developed a model of the activities of the teams, based on the description of a planned mission traverse.

Purpose of the Victoria model

The major limitation of current robot energy modeling tools, apart from model maintenance, is the inability to include human factors in the calculations of the power consumption of the rover. Before our case study, the influence of earth-based operations practice on the energy usage of the rover was unknown. The purpose of the case study was to a) prove that we could model this complex work system and b) determine the effect of a particular work system design on the power consumption of the rover during a science traverse into a permanent dark crater.

The model prescribes a work system design by incorporating a model of the locations and movement of the rover and teams, activities of all the Earth-based teams, the rover, their communication actions, as well as the hardware and software systems that are used. Next, we give a brief description of the design of the Victoria work system. For a more detailed description we refer the reader to chapter 8 in [23].

Agent model

Figure 5 shows the group membership hierarchy on which the design of the work system is based. The agents in the model are the Earth-based human teams and the Victoria rover, as shown in Figure 4. The teams are represented as single agents, because at this moment it is not possible to prescribe the composition and practices of each team in more detail. For example, the “plan a command sequence” activity of the SOT represents the work of the team, while the individual activities of each team member remain unspecified.

[FIGURE 5 HERE]

The VictoriaRover is modeled as an agent because it has activities, including primitive actions that change the world, movements, and communications².

Table 1 shows a possible distribution of the functions over the Victoria teams [28]. Details of how different teams collaborate to perform these functions constitute the work practice, specified in Brahms *workframes* of the different agents.

[TABLE 1 HERE]

² Strictly speaking, activities of designed objects are only formal processes. Activities of people are conceptualizations. However in a Brahms model both are abstractions in a formal language, so the distinction is how we interpret the model, what it represents, rather than how the simulation operates.

An example workframe for the Data Analysis and Interpretation Team (DAIT agent) is interpreting the hydrogen data being downlinked by the Victoria rover, when it is detecting hydrogen.

```
workframe wf_InterpretHydrogenData {  
    variables:  
        foreach(Data) nd;  
    when (knownval(current.notifyUser = interpretdata) and  
        knownval(VisualizationSystem.neutronDetectorData = nd))  
    do {  
        InterpretHydrogenData(110, nd);  
        conclude((current.notifyUser = receivedhydrogendata);  
    }  
}
```

The workframe states that if the DAIT agent believes that it needs to interpret science data and the DAIT agent believes that the data visualization system has neutron spectrometry data available, the DAIT agent will start the interpretation of the Hydrogen data. Once it is done with the interpretation it believes that it has received new hydrogen data, which will make the DAIT agent communicate this information to the SOT agent (not shown).

Object Model

A Brahms object model consists of the classes and instances of physical artifacts, as well the data objects created during the simulation. The Victoria object model, shown in Figure 6, includes classes for the science instruments on the rover, as well as other

objects contained in the rover, such as the carousel and the battery. The data communicator class includes the objects for S-band and Uhf communication. The model also represents software systems that receive, convert, and visualize mission data. The Data and CoreSample classes dynamically create data instances and lunar core sample objects during the simulation.

[FIGURE 6 HERE]

For example, the uplink command for the Victoria rover contains a dynamically created data object containing beliefs that represent the command sequence data being uplinked.

```
CommandSequence2 instanceof Data {  
    (VictoriaRover.nextActivity = SearchForWaterIceInPermanentDarkAreaActivity);  
    (VictoriaRover.subActivity = projects.victoria.DrillingActivity);  
    (SATM.lengthIntoSurface = 10.0);  
    (SATM.sampleVolume = 1.0);  
}
```

In the above example the CommandSequence2 data object contains two commands. The first to tell the rover its next activity is to search for water ice. This will put the rover in a water ice search state. The second command is a sub-activity command stating that the rover should start a drilling activity in which it should drill for 10 cm into the lunar surface and then should take a 1.0cc sample (the SATM object is the lunar surface drill on the rover).

Geography Model

The Victoria geography model, shown in Figure 7, represents locations on the Earth and Moon (cf. Figure 4). The dotted lines in Figure 7 show class-instance relationships, whereas the solid lines show part-of relations.

[FIGURE 7 HERE]

The Victoria teams and systems are located in Building244; the UsnDish1 satellite dish is located in the area UsnSatelliteLocation. Locations for the simulated scenario are represented on the Moon (described in the next section): ShadowEdgeOfCraterSN1 represents the location of the rover at the start of the simulation (the shadow edge that is in crater SN1). ShadowArea1InCraterSN1 represents the location in the permanent shadowed SN1 crater where the rover will perform a drilling activity. The LandingSite area is only represented for completeness.

Victoria Model Simulation Results

The simulation provides visibility into the behavior of the work system over time, that is, activities, communication, and movement of each agent and object. After the model is developed and compiled, the Brahms simulation engine executes the model. A relational simulation history database is created, including every simulation event. An end-user display tool called the *AgentViewer* uses this database to display all groups, classes, agents, objects, and areas in a selectable tree view. The end-user can select the agents and objects he/she wants to investigate. The *AgentViewer* displays a workframe-activity hierarchy time line of the agents and objects selected, optionally showing agent and object communications. Using this view the end-user can investigate what happened during the simulation (see Figure 8). For an explanation of the *AgentViewer* see Appendix: AGENTVIEWER EXPLANATION SHEET.

[FIGURE 8 HERE]

In addition to the timeline output from the *AgentViewer*, we are able to generate statistical data graphs based on calculations made during simulation. The same relational

simulation history database used for the AgentViewer display was used to generate graphs. We generated energy consumption of the robot based on the uplink command from the Vehicle Spacecraft Operations Team in Figure 8 (see Figure 9).

[FIGURE 9 HERE]

The Victoria case study shows how Brahms can be used to model and analyze operations for new robotic mission proposals. We are able to show the effect of the work process of Earth-based teams on activities and energy consumption of the rover. By combining models of work activities, decision-making, communication, location and movement of people, as well as activities of the robot, mission critical systems and mission data, we were able to simulate the complex interactions between all the components in the work system. The benefit of the approach lies in the ability to show how the relations between all the elements change over time through agent interaction. The simulation allows mission designers to compare different work system designs during the proposal phase and provides guidance to mission and robot designers, replacing a spreadsheet approach by a more transparent, flexible, and reusable multiagent simulation and work process representation.

Next, we discuss how the Brahms modeling and simulation approach is being used for mission operations work system design for the next robotic mission to Mars. Whereas the Victoria mission was in the proposal stage and not selected to become an actual mission³, the MER mission is a funded mission and is currently in its design and implementation phase.

³ There are many mission proposals submitted for robotic space exploration. The chance for a mission proposal to be selected to become a funded NASA mission is less than five percent.

MER Mission Operations Work System Design

The Mars Exploration Rover (MER) mission to the surface of Mars is a dual-robot mission with unprecedented capability (Figure 10). With a complement of remote sensing and in-situ science instruments, and the ability to traverse a distance in one day roughly equivalent to the distance traversed by Pathfinder's Sojourner Rover over its entire mission lifetime, the MER Rovers provide new operational capabilities and challenges. The MER mission is planned to start in December of 2003 with the launch of the MER-A rover. One month later the MER-B rover will be launched. The Jet Propulsion Laboratory (JPL) in Pasadena, CA operates the MER mission (Figure 11). At the moment of writing this paper, the MER mission operations systems (MOS) design team is still working on designing and testing some of the mission operations concepts.

[FIGURE 10 HERE]

Based on the results from the Victoria case study, the Brahms team was asked to model the work process of the MER mission to analyze the design of the mission operations work system. Initially, analysis reports generated from a Brahms simulation are being used in two ways: to develop procedures for the different organizational roles and activities and to verify these procedures during their intermediate operations field tests at JPL.

[FIGURE 11 HERE]

The next section describes the Brahms MER model design and its use during the ongoing MER mission operations work system design phase.

MER Mission Operations Challenges

The planned operational lifetime of each rover on the surface is ninety days. To exploit the capability of each rover requires two complete separate teams of scientists and

engineers to receive and analyze data, develop science strategies, and uplink movement and instrument commands on a daily basis. To synchronize the activities on Earth with those of the rovers on Mars, the mission clock in Pasadena, including the MOS process, will be on Mars time. With a landing separation of roughly one month, there will be a significant period of dual rover operations, most likely in different Mars time zones.

The MER MOS team at JPL is responsible for developing an integrated work system to operate the MER rovers. This system includes the people, operations processes, procedures, and tools (see Figure 12). Based on daily analysis of newly returned data, scientists will develop strategies for acquisition of more data. Engineers develop strategies to operate the rover. Together, they develop time-ordered and constraint-checked sequences of activities, which are then transformed into commands and uplinked to the rover. Throughout, the MOS team must keep the rover safe and maximize its productivity.

[FIGURE 12 HERE]

The challenge facing MOS designers is to make people, processes, tools and procedures work together in an operational environment that has never been attempted before—dual rover operations on the Martian surface. To test and verify the system design, training exercises called operations readiness tests (ORTs) will be performed few months prior to landing on Mars. At that point it is too late to make any fundamental changes in the system software design, though procedural changes may still be accommodated. Given the mission critical nature of the operations system, and the limited opportunities for early testing and verification, an effective set of tools to aid in the development and verification of the system early in the design process—when

fundamental design changes are still possible—could greatly increase the efficiency and productivity of a mission operations system. Current tools create static representations of people, procedures and events, and do not take into consideration dynamic interactions among different elements of the work system. An integrated view of the relationship of the ground system design to the space system design is also not possible with current tools.

A more complete representation of work system elements, simulating the interactions between people, objects and geography in a complete work system, including a model of the rover, has the potential to assist mission operations system designers in creating designs that are safer and more efficient. The next section describes our human-centered approach to the design of the MER work system. The approach is based on socio-technical systems approaches from the sixties and seventies, as well as the participatory design approaches from the eighties [25].

Participatory Design

A number of work design approaches have been described in the past decade. Most of them are developed through qualitative research in interdisciplinary academic fields that combine social science with systems analysis [15]. The wave of Scandinavian participatory design projects in the late eighties [9] epitomizes this approach.

In redesigning a work system the designers have to understand how the work is actually performed. In the case of the MER mission operations this is difficult, because the work system will be largely new. Therefore, we apply the central principle of participatory design by forming a joint design team [12]. Because computer scientists are largely unknowledgeable about mission operations for robotic missions, including

experienced JPL mission operations personnel in the redesign process is essential for influencing and successfully designing MER operations. Indeed, our JPL colleagues might say the converse is true, too, that they require the methods of work systems design, modeling, and simulation to succeed.

Given that the MER MOS exists only as a design specification that is still evolving and changing rapidly, how do we model and simulate it? We considered building the model based on high-level work process specifications from JPL, however this had several shortcomings, including the rapidly changing nature of the design and the difficulty in keeping the documentation up to date. This is a well-known problem in software engineering, and is one of the reasons why a model-based design approach is helpful [16]. The modeling effort not only documents the design, it also drives the analysis and design process itself [21]. We decided to conduct interviews with key MER team members, asking them to describe their future MER job activities, information needs, interfaces and tools. Based on this data we were able to build a simulation model showing the key MOS positions as agents, their interactions with other agents and objects, and the need for specific information during their activities.

After the first model was developed, we went back to the team members to verify the model. In our first model, by comprehensively relating multiple agents acting at different times and places, we were already able to reveal some discrepancies in what the different team members described as their work activities and information needs. Specifically the interaction between key people during meetings and informal information exchanges was shown to be problematic (described below).

A key aspect of our participatory design approach is to have the simulation be actively used by the MER team during mission operations reenactments. During these reenactments the output from the simulation (activities, timelines, information flow and communication) is shown on a large computer-based white board called the MERBoard (see Figure 13).

[FIGURE 13 HERE]

Scientists and engineers can use this display to display the simulation, verify their personal activities, and correct the model. Thus, the output from the simulation model serves two purposes; 1) it serves as a reminder of what the person is supposed to be doing—much like a procedure, and 2) it allows the MER MOS team to change the design of the work system during the reenactment, by directly annotating the simulation output.

In summary, we apply a participatory approach to simulation-based work systems design. As is common in work environments, it is not possible to add to the JPL team's workload. Developing the simulation model so it is integrated with and supports the already occurring design process enables modelers to participate in the design process, and provides the MER team with data that they would otherwise not have. Because our model is based on the team's own perceptions of the work as described in interviews and during reenactments, the team has an inherent interest in seeing the results, and participates in refining the design through the model. Others have described this problem in business reengineering projects a decade ago [20].

Modeling and Simulation Tools for Mission Operations Design and Support

In this last section of the paper, we describe the design of the MER Brahms model in more detail. We contrast each MER model component with the Victoria model. The

reader is reminded that the Victoria model was a first case study of using Brahms for designing a work system for a robotic mission. Given the positive result of this case study, we started to apply our method to MER, an actual mission. Although we were confident that we could model and simulate the mission operations for the MER mission, we had no experience in affecting a real work systems design effort. We started the effort with the Victoria model as our guiding principle, changing this model to represent more detailed mission practices. Hence, it is useful in describing the MER model to draw contrast with Victoria. The last subsection presents the output of the MER MOS simulation and discusses what it reveals.

Agent Model

The agent model is based on JPL's organizational design of the MER mission operations team. The group membership hierarchy of the model is shown in Figure 14. Like the Victoria model, the agents modeled are within the Earth-based mission operations teams and the Athena rover. Only key positions within each team are modeled as agents, because the details of the composition of each team are still being identified as the design of the MER MOS continues. Also, the work practices of these key team members are not completely known at this time. However, in contrast with agents representing whole teams in the Victoria model, agents in the MER model represent specific individuals. Five Science Theme Groups lie within the Science Ops Working Group. Each serves as a forum for discipline-specific science analysis, discussion, and planning. Only two of the five science theme groups are modeled currently; the anticipated work practice of the other groups is assumed to be similar. As in the Victoria

model, the Athena rover is modeled as an agent because it has activities, including primitive actions that change the world, movements, and communications.

[FIGURE 14 HERE]

As in the Victoria model, MER agents participate in two main processes—downlink and uplink. The downlink process consists mainly of collection, enhancement and analysis of data returned by the rover. Besides building commands for the rover to execute, the uplink process also includes decisions and trade-offs to satisfy both science and engineering goals, based on available image and instrument data. Table 2 shows the functional activities distributed among the MER Operations teams in each process. As in the Victoria model, the details of agent activities constitute the work practice, specified in workframes.

[TABLE 2 HERE]

On close inspection of the MER and the Victoria agents' functional activities, similarities can be seen in respective groups. The MER and the Victoria group hierarchies are almost equivalent (Table 3).

[TABLE 3 HERE]

The Victoria agent model is less detailed than the MER agent model, because of the proposal stage of the Victoria project. MER is an actual mission, so more operations have been thought through and documented.

Object Model

As in the Victoria model, the object model for MER consists of classes for physical objects, artifacts and data, plus dynamically created instances of data (Figure 15):

- Science instruments and the instrument deployment device on the rover, which all consume energy.
- Communication devices for both S-Band and UHF data, between the Earth-based team and the rover on Mars.
- Software systems (Ground Data Systems) to receive data from the rover, convert data for analysis and archival by the Earth-based team, and send command data to the rover.
- Information about rover health and measurements taken by instruments on board.

[FIGURE 15 HERE]

The MER object model expands upon Victoria by replacing the Data Conversion System with the Data Acquisition Command Subsystem and the Operations Product Generation Subsystem, based on the actual systems being developed (c.f. Figure 6). Also, Victoria's Tele-Operation System is contained within the Engineering Analysis Subsystem and Victoria's Visualization System is part of the Activity Planning Sequencing Subsystem, which provides both visualization and rover activity planning and sequencing functionality.

[TABLE 16 HERE]

Figure 16 shows a further expansion of Victoria's data object model for MER. In addition to the objects representing data returned by the rover, the model now includes representations of statically and dynamically created reports and activity plans by the Earth-based teams. The model will eventually include the fields contained in these reports and how this information could affect rover activity planning

Agent Beliefs

Unlike the agents in the Victoria model, the agents in the MER model are individual people (their names are invented and do not denote real people at JPL). Consequently, the MER model has a higher level of detail, which results in a larger belief set for the individual agents. Figure 17 shows part of the inherited attributes for the geology science theme lead agent (MA_Geology_Lead). Attributes are used to define what beliefs (and facts) can be created about the agent. For example, agents that are members of the MER_Mission_Team group can have beliefs about the time of day on Earth (perceivedHour, perceivedMinute in Figure 17), as well as the current and previous Mars Sol number (thisSolNum, prevSolNum).

[FIGURE 17 HERE] AND [FIGURE 18 HERE]

Figure 18 shows the initial beliefs that the MA_Geology_Lead agent gets at the start of a simulation⁴. Since the MA_Geology_Lead agent is a member of the MER_Mission_Team group, it inherits all the initial beliefs defined at that group level. The initial beliefs of agents and objects define the start state of a simulated scenario. Figure 18 shows that the agent believes that the simulation starts at midnight on Mars and at Mars Sol two (i.e. the second mission day on Mars).

Activities and Workframes

Space withholds us from giving an extensive overview of the agent and object's activities and workframes. We will only give one example so that the reader gets an idea of the detailed agent behavior in the model.

⁴ This and the next three figures are screenshots of the MER Agent Model, displayed in the Brahms IDE.

Every science theme lead needs to be at the Science Ops Working Group (SOWG) meeting that is held at 7pm every Sol. The SOWG meeting is *the* meeting where the science team decides what to do in the next Sol.

[FIGURE 19 HERE] AND [FIGURE 20 HERE]

Figure 19 shows the SOWG_Meeting composite activity in the Science_Theme_Lead group. Every member agent of the group will inherit the activity and thus has the ability to attend and participate in the SOWG meeting. As described in the Brahms Language section, an agent cannot just execute an activity. The SOWG_Meeting activity needs to have a workframe that constraints when the activity can be performed. Figure 20 shows this SOWG_Meeting workframe also defined in the Science_Theme_Group. The preconditions state that when the agent believes that the clock in the his office (“clk.location = current.MyOffice” in Figure 20) shows that it is 7pm (“clk.hour = 19”), the workframe becomes active and based on priority scheduling of the engine the agent will perform the SOWG_Meeting activity. This simulates that the agent must actually “see” (i.e. detect) that the clock’s time shows 7pm, which means that the agent must be in his office to actually get this belief. It also means that if the agent does not detect the time the agent will not be at the meeting, and if the agent detects the clock’s time late (i.e. after 7pm) the agent will be late for the meeting. Thus, whether the agent shows up for the meeting and when is a consequence of the dynamics of the simulation. The principal science investigator told us that if he is chairing the meeting, the SOWG meeting *will* start on time regardless who is there. This behavior is implemented in the model, and the simulation shows the influence of this practice.

Geography Model

As in the Victoria model, locations on Earth and Mars are represented.

[FIGURE 21 HERE]

Figure 21 shows Hematite, the planned landing site of the Athena rover. At the start of the simulation, the rover is located at this landing site. The Earth-based teams are housed in Building A and Building B⁵. The engineering team is in a large room in Building A. The instrument or “payload” teams and the science teams are in Building B. Each instrument team has a separate room, however science teams are placed together in a single large room. The conference room, where the science teams, engineering teams and the instrument teams meet, is located on a separate floor within Building B. Modeling an agent’s location and movement within Building B has required a more detailed representation than in Victoria model; part of the representation is shown in Figure 22.

[FIGURE 22 HERE]

The geography model includes the travel time between each room in and between buildings. In this way, the simulation can keep track of each agent’s travel time to meeting rooms, showing the influence of the layout design of the buildings on operations efficiency.

MER Simulation Scenario

As for Victoria simulation, the objective of the MER simulation is to understand the communication and interactions between people holding key positions within the

⁵ Due to the sensitivity of the information, the actual MER Building names and numbers are changed.

earth-based mission operations teams for a twenty-four hour period, outlined in this scenario:

The rover has been at the planned landing site called "Hematite" for one sol (a Martian day). During that sol, the rover used its panoramic camera, henceforth known as the Pancam, to take a picture of its surroundings and also uses its Mini-Thermal Emission Spectrometer, henceforth known as the Mini-TES, to penetrate through dust coatings, looking for carbonates, silicates, organic molecules and minerals that are formed in water on the surface of Martian rocks. As evening approaches on Mars, the rover sends the panoramic image taken by the Pancam and data gathered by its Mini-TES back to the mission operations team on Earth.

The data is first received by the engineering and payload teams for enhancement. After data enhancement, analysis of the data is carried out by these teams to determine what health and configuration activities needs to be carried out by the rover and its payload for the next sol.

At the same time, the data is made available to the two different discipline-specific science teams. Each discipline-specific science team analyzes the data for possible scientific investigations to be carried out in the next sol. The two discipline-specific science teams get together to discuss their respective science discoveries and together they identify a science target for the next sol. The science target is picked because the initial panoramic Mini-TES data indicates the possible existence of a mineral formed in water on its surface.

After analysis by the engineering, payload and science teams is completed, they get together to exchange information. The engineering and payload teams share information about the health and safety constraints of the rover and its payload while the science team give their scientific intent for the next sol. With the understanding of the information presented by the engineering and payload teams, the science teams present their rational to approach the target identified previously in order to get a closer image and Mini-TES reading.

At the end of the discussion various people leave the room and only a core group of people from the engineering, payload and science teams remain behind. This core team discusses the final combination of the various activities, proposed by each team, for the rover to perform in the next sol. Trade-offs between

engineering and science activities are discussed and a final sequence of high-level commands for execution are formed. The sequence of high-level commands will then be translated into lower-level commands that the rover understands.

By the time this sequence of high-level commands is formed, most people would have worked approximately ten hours and a second group of people will come to take over the translation of commands and transmission to the rover. Each person in a key position will go off and hand over information to their corresponding person in the same position before heading home.

Finally, the second shift of people build and transmit the commands to the rover.

Simulation Results

As in the Victoria model, the simulation provides a visible representation of the activities in the work system over time. Using the AgentViewer tool to show events that happen during the simulation on a timeline format has revealed interesting communications behavior in the initial design of MER operations.

Communication Activities

Synchronizing communication between key personnel was identified as being important during the collaborative modeling effort between the Brahms modeler and the mission operations design team. Indeed, the simulation output showed some problems. Figure 23 shows that, after performing an initial “quick health check of rover”, the Tactical Downlink Lead tries to “confer with SOWG” Chair to provide an update of the status of the rover’s health. Unfortunately, the Science Ops Working Group (SOWG) Chair is still at home and not available to receive this update. When the SOWG Chair arrives at the Science Work Room, the SOWG Chair tries to “understand state of rover” by requesting information from the Tactical Downlink Lead who is not available, because (s)he is busy trying to get a “preliminary engineering activity plan update” from the

engineers in the Mission Support Area. Without information about the status of the rover—information that may be crucial when problems occur—the simulation shows the SOWG chair nevertheless proceeding to meet with the science theme group members to decide about the science investigations for the next sol.

[FIGURE 23 HERE]

Handover Activities

The mission operations design team has been concerned about the fatigue of people in key positions. These people will work about ten hours from the moment they receive data from the rover until making a decision about what the rover should do for the next sol. The mission operations design team decided that a second shift of people fulfilling the same key positions will be necessary to relieve the duties of the first shift. Considerable work systems design effort focuses on providing the second shift with the contextual information they need to quickly take over the duties of the first shift. One of the early recommendations from this study is to provide the second shift not only with a verbal face-to-face update, but also to hand over a report. Figure 24 shows the verbal face-to-face communication of information in the Science Work Room between the SOWG Chair and the Science Uplink Representative during “Debrief shift 2.” The SOWG Chair tells the Science Uplink Representative what science investigations the science team has agreed upon and what rover and payload activities need to be carried out in the next sol. All this information was previously discussed during the “SOWG Meeting” and documented in the “MER A Sol 2 Science Activity Plan,”

[FIGURE 24 HERE]

Movement Activities

The mission operations design team is aware that locating people who need to interact with each other in close proximity will be important during the mission. In the design, the engineering team is in Building A and the science team on the Xth floor of Building B. The conference room, where meetings are held, is on the Zth floor of Building B. The simulation reveals, as shown in Figure 25, how people spend a significant amount of time traveling to the conference room to hold a meeting, which is two floors above the floor where they perform most of their work. The facility plans mention that during the mission, security devices will be installed on doors to restrict access from floor to floor within a building. These security doors will further increase the time required for people to move. In light of the simulation, the mission operations design team decided to move the engineering team from Building A to the Xth floor in Building B, the same building and floor as the science team.

[FIGURE 25 HERE]

Reports Generated

A relational database, including every simulation event, is created when Brahms' simulation engine executes the model. This database allows reports and statistical information to be generated for analysis. In particular, the mission operations design team requested a daily schedule for every key position, which we provided from the simulation output by using database queries. For example, Figure 26 shows every activity that the Tactical Downlink Lead position will perform during a day of mission operations.

[FIGURE 26 HERE]

Besides scheduling activities for every key position, the mission operations design team also wants to ensure that information and reports that each key position needs are available when required. Another report was generated from the Brahms simulation database to assist in the mission operations design team's effort, shown in Figure 27.

[FIGURE 27 HERE]

Conclusions

In this paper we described how Brahms is used to design a work system for semi-autonomous robotic mission operations. The simulations show the influence of the work practice of Earth-based teams on activities and energy consumption of the rover and allow mission designers to compare different work systems, before critical mission decisions have been implemented.

The multiagent, object-oriented activity-based approach of Brahms, including explicit representations of geography, systems, and data, reveals the interaction of facility layouts, schedules, reports, handovers, and procedures.

We have presented a collaborative work system design methodology incorporating simulation of work practices. The Brahms modeling framework provides guidance to mission and robot designers, replacing a spreadsheet and informal design approach by a participatory approach that represents the total work system in a formal model with adjustable levels of detail. We illustrated the representational capabilities of the Brahms environment by describing its use for both the Victoria proposal and the actual MER mission design.

The purpose of the simulations is to show the dynamics and interactions between individual entities (people and machines) in the work system, as well as calculate

duration time, energy consumption and other relevant statistics. Being able to show how a work system will behave over time before it has been implemented provides work system designers with a powerful design tool. Formalizing and then simulating work practice descriptions creates a deeper understanding of the dynamic relationships that exist in the system. Indeed, being able to show the obvious in excruciating detail can be a powerful reminder of how the design influences how the system with its problems develops over time. The results from the MER simulation shown in the previous sections might seem obvious to the reader, and one might question its benefits. Indeed, the problems are not especially complex and might have been discovered without the simulation. However, the fact remains that dysfunctional work systems are commonplace. Our intent is to provide a tool for reflecting on a design and anticipating problems. For example, before the simulation included the geography model the MER mission operation designers did not believe that separating the teams and conference rooms into different buildings would cause difficulty. They may have noted the distance and security doors that had to be negotiated, but they accepted the design without concern. The simulation calculates how much time is actually lost, and thus is able to characterize and formalize the implications of this "obvious" feature. Without a simulation, interacting tradeoffs are difficult to evaluate, and only opinions prevail. The simulation output has brought this to the mission design team's attention. The building design is being changed in part due to the simulation.

The models described in this paper might not at first seem relevant for more traditional organizations. Indeed, the mission operations work systems for robotic missions are non-existing, special-case, short-term organizations that exist only for the

duration of a mission (in case of the MER mission only for 90 days). However, we have shown that both the organizational and information management issues are similar to those in conventional business organizations. The SOWG meeting example in the MER model can be seen as any daily business meeting in a traditional organization, similarly for the use of the information systems. We are therefore convinced, besides the fact that Brahms research was from the start grounded in the telephone company domain, that the Brahms framework is directly applicable to other types of organizations. In particular, when an organization already exists a descriptive modeling phase is possible. This enables analyzing organizational change by showing the effects of a process redesign on the existing organization at the level of the work practice (as opposed to only showing a static normative workflow).

We emphasize that our approach, using Brahms, provides substantive grounding when a design team includes people who will be doing the future work. Combining modeling with participatory socio-technical design allows both teams—the modelers and the workers—to engage in a joint design effort. Without the notion of partnership and co-design from the start, the Brahms model could not have meaningful content and the results might not be examined and used. Hence, the Brahms tool is not just a way of representing work, but an instrument for forming and sustaining an effective multidisciplinary team.

Appendix: AGENTVIEWER EXPLANATION SHEET

[FIGURE 28 HERE]

- a) Using the menu-bar, the end-user can parse the simulation history data into a history database, and open a history database for viewing.
- b) When the database is opened all the agents and objects are loaded into the tree view. Using the tree view, the end-user can select which agents and/or objects (s)he wants to view in the time-line view.
- c) By selecting to view the agent/object communication, the (blue) arrows show all the communication activities, and the direction of the communication (sender and receivers). The communicated beliefs are also accessible by clicking on the square at the top of the sender side of the communication arrow.
- d) For each agent/object the "current" location is shown. When the agent/object moves to a new location, it is shown as a change in the location name and color.
- e) The time-line can show the time in different time-intervals, therewith zooming in and out.
- f) The tool-tip pops up when the mouse is moved over "hot spots". The hot spots are those areas where more information is available than can be shown on the screen. By moving the mouse over those areas the hidden information pops up in a tool-tip, such as the name of a workframe or activity.
- g) The Activity-Context Tree is the central piece of the agent/object time-line. It shows the workframe and activities hierarchy of the agent or object.

- h) The touch-object line is a (yellow) line that is shown when the agent/object is using certain objects in its activity. "Touch objects" are used to calculate the time those objects are used in activities.
- i) The explanation facility view is used to display more detailed information about the execution of workframes. By clicking on any workframe (light blue in color), an explanation facility window is opened for the workframe at hand.
- j) By selecting the "Active" tab in the explanation facility view, the executed statements in the workframe body are shown.
- k) You can select the statements in the workframe body to get more info.
- l) When you select a statement in the body of the workframe, the total time the activity was active is shown. Using the other tabs in this view, you can find out the exact time the workframe became available, as well as the exact time it became active and ended.
- m) Workframes are situated-action rules that execute activities. The top of a Activity-Context tree is always a workframe. You can recognize a workframe by the "wf:" symbol, followed by the name of the workframe. When the zoom-level is too high to contain the name of the workframe it is left out of the display. Using the tool-tip the user can find out the name.
- n) Composite Activities are executed by workframes, and contain lower-level workframes. You can recognize Composite Activities by the "ca:" symbol followed by the name of the activity. When the zoom-level is too high to contain the name of the activity it is left out of the display. Using the tool-tip the user can find out the name.

- o) Primitive Activities are executed by workframes, and are always at the bottom of the Activity-Context Hierarchy. You can recognize Primitive Activities by the following symbols, depending on the type of primitive activity: “pa:” (for a primitive activity), “mv:” (for a move activity), “cw” (for a communicate activity), “co:” (for a create object activity), followed by the name of the activity. When the zoom-level is too high to contain the name of the activity it is left out of the display. Using the tool-tip the user can find out the name.

References

1. Clancey, W., J. *Situated Cognition: On Human Knowledge and Computer Representations*. Cambridge University Press, 1997.
2. Clancey, W.J. The Conceptual Nature of Knowledge, Situations, and Activity, in P. Feltovich, R. Hoffman, and K. Ford, ed., *Human and Machine Expertise in Context*, Menlo Park, CA: The AAAI Press, 1997, 247-291.
3. Clancey, W.J. Developing learning technologies in practice, in C. Bloom and R.B. Loftin, ed., *Facilitating the Development and Use of Interactive Learning Environments*, Hillsdale, NJ: Lawrence Erlbaum Associates, 1998, pp. 3-20.
4. Clancey, W.J. Simulating Activities: Relating Motives, Deliberation, and Attentive Coordination. *Cognitive Systems Research*, 3, 3, (2002), 471-499.
5. Clancey, W.J.; Sachs, P.; Sierhuis, M.; and van Hoof, R. Brahms: Simulating practice for work systems design. *International Journal on Human-Computer Studies*, 49, (1998), 831-865.
6. Cornell, <http://athena.cornell.edu/>. 2001, Cornell University:
7. Davenport, T.H. *Process Innovation: Re-engineering Work through Information Technology*. Boston, MA: Harvard Business School Press, 1993.

- 8.Davenport, T.H. The fad that forgot people, *Fast Company*, Vol. 1995, No. 1, November 1995 (1995),
- 9.Ehn, P. *Work-Oriented Design of Computer Artifacts*. Stockholm, Sweden: Arbetslivcentrum, 1988.
- 10.Emery, F.E., and Trist, E.L. Socio-Technical Systems, in C.W. Churchman, ed., *Management Sciences, Models and Techniques*, London: Pergamon, 1960.
- 11.Goodall, K., <http://mars.jpl.nasa.gov/missions/future/2003.html>. 2002, JPL:
- 12.Greenbaum, J., and Kyng, M., ed., *Design at Work: Cooperative design of computer systems*, Hillsdale, NJ.: Lawrence Erlbaum, 1991.
- 13.Hammer, M., and Champy, J. *Re-engineering the Corporation*. New York, NY: Harper Collins Publishers, Inc., 1993.
- 14.Hintikka, J. *Knowledge and Belief*. Ithaca, NY: Cornell University Press, 1962.
- 15.Holtzblatt, K., and Jones, S. Contextual Inquiry: A Participatory Technique for System Design, in A. Namioka D. Schuller, ed., *Participatory Design: Principles and Practices*, Hillsdale, NJ.: Lawrence Erlbaum Associates, 1993, p. 177-210.

16. Jacobson, I. *Object-Oriented Software Engineering: A Use Case Driven Approach*. Object Technology Series, Reading, MA: Addison-Wesley Publishing Company, 1994.
17. Konolige, K. A first-order formalization of knowledge and action for a multi-agent planning system, in J.E. Hayes, D. Mitchie, and Y. Pao, ed., *Machine Intelligence*, Vol. 10, Chichester, England: Ellis Horwood, 1982, 41-72.
18. Konolige, K. *A Deduction Model of Belief*. San Mateo, CA: Morgan Kaufmann, 1986.
19. Pava, C.H.P. *Managing New Office Technology: An Organizational Strategy*. New York: The Free Press, 1983.
20. Sachs, P. Transforming Work: Collaboration, Learning, and Design. *Communications of the ACM*, 38, 9, (1995), pp. 36-44.
21. Schreiber, G.; Akkermans, H.; Anjewierden, A.; Hoog, R.d.; Shadbolt, N.; Velde, W.v.d.; and Wielinga, B. *Knowledge Engineering and Management: The CommonKADS Methodology*. Cambridge, MA: The MIT Press, 2000.
22. Shoham, Y. Agent-oriented programming. *Artificial Intelligence*, 60(1), (1993), 51-92.

23. Sierhuis, M. *Modeling and Simulating Work Practice; Brahms: A multiagent modeling and simulation language for work system analysis and design*, Ph.D. thesis, University of Amsterdam, SIKS Dissertation Series No. 2001-10, (2001).
24. Sierhuis, M., and Clancey, W.J., Knowledge, Practice, Activities, and People, Brian Gaines. 1997, Proceedings of AAAI Spring Symposium on Artificial Intelligence in Knowledge Management: Stanford University, CA. 142-148.
25. Sierhuis, M., and Clancey, W.J. Modeling and Simulating Work Practice: A human-centered method for work systems design. *IEEE Intelligent Systems*, Volume 17(5), Special Issue on Human-Centered Computing, (2002),
26. Thomas, G.; M. Reagan; E. A. Bettis III; N. Cabrol; and Rathe, A. *Analysis of science team activities during the 1999 Marsokhod rover field experiment: Implications for automated planetary surface exploration*, The University of Iowa, (1999).
27. van Hoof, R., and Sierhuis, M., Brahms Language Reference, http://www.agentisolutions.com/documentation/language/ls_title.htm, 2000, NASA/Ames Research Center:
28. Wall, S.D., and Ledbetter, K.W. *Design of Mission Operations Systems for Scientific Remote Sensing*. London: Taylot & Francis, 1991.

29. Weisbord, M.R. *Productive Workplaces: Organizing and Managing for Dignity, Meaning, and Community*. San Francisco, CA: Jossey-Bass Inc., Publishers, 1987.

30. Wooldridge, M. *The logical Modelling of Computational Multi-Agent Systems*, Ph.D. thesis, Department of Computation, UMIST, (1992).

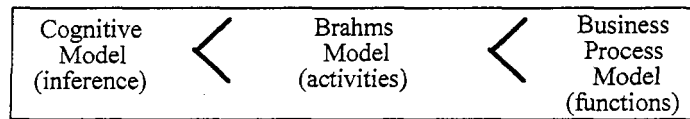


Figure 1. Relation of Brahms models to other models

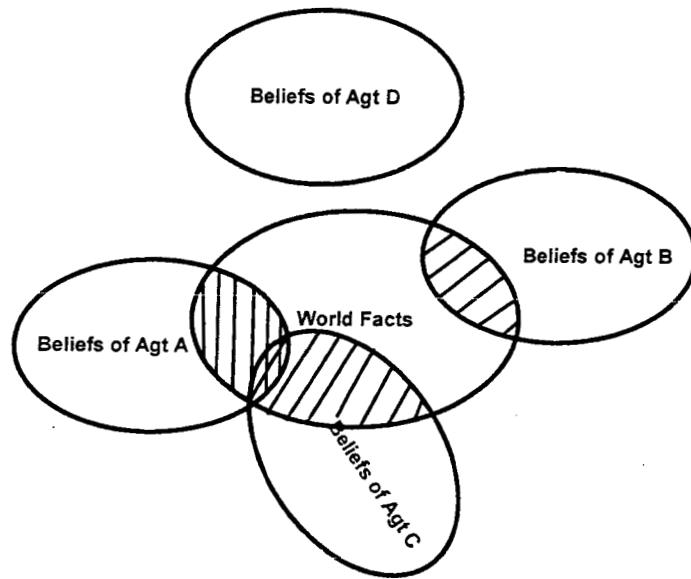


Figure 2. Beliefs and facts Venn diagram

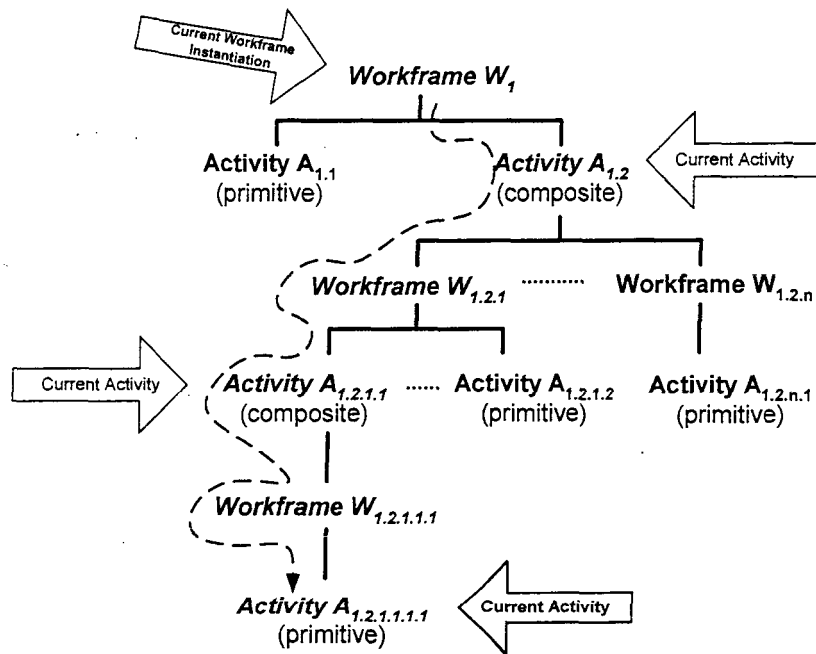


Figure 3. Workframe-Activity hierarchy

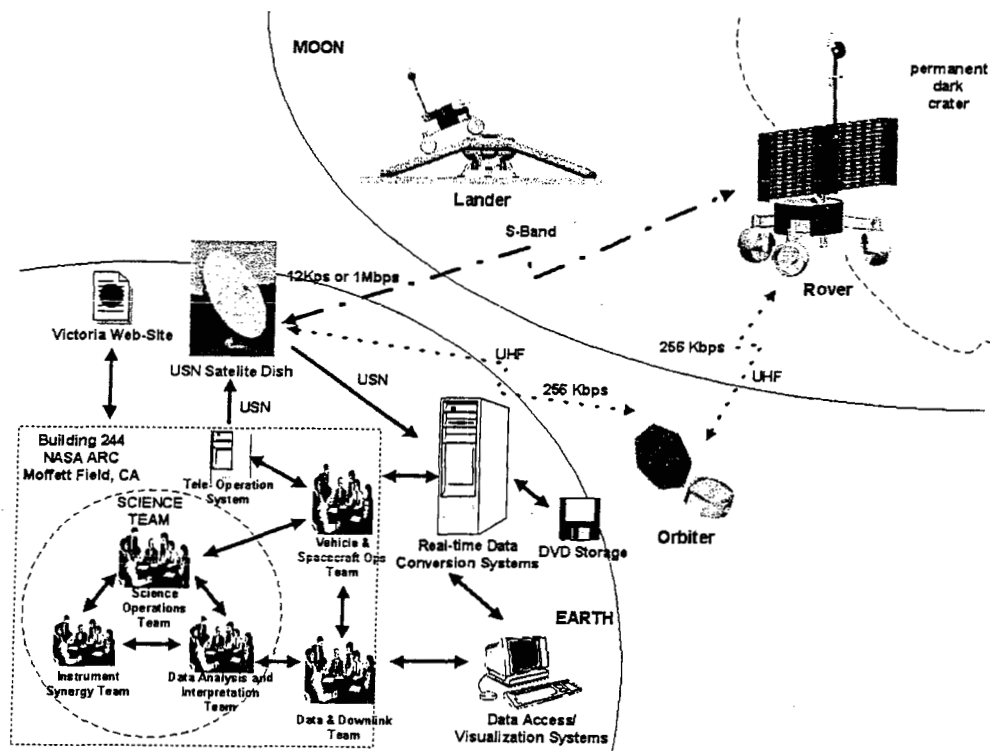


Figure 4. Victoria mission operations work system

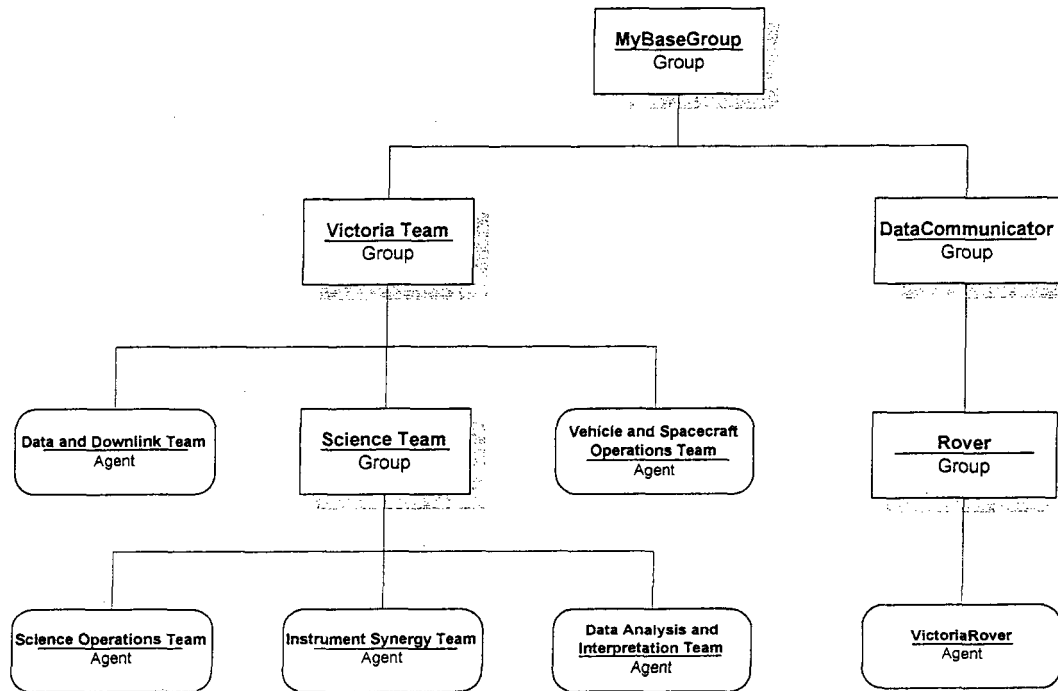


Figure 5. Victoria Agent Model

Table 1. Functional activity distribution over Victoria teams

	Science Operations Team	Instrument Synergy Team	Data Analysis and Interpretation Team	Data and Downlink Team	Vehicle and Spacecraft Operations Team	Rover
Uplink process	1. Maneuver commands 2. Command sequences for experiment operation	1. Commands for engineering operation of robot/spacecraft 2. Emergency or anomaly resolution commands	1. Long-term planning for science opportunities	1. Tele-communications commands	1. Maneuver commands 2. Command sequences for experiment operation	1. Command execution
Downlink process		1. Monitoring of health and status telemetry from robot subsystems	1. Data quality assessment 2. Experiment data collection	1. Experiment data collection 2. Data processing and enhancement		1. Experiment data collection

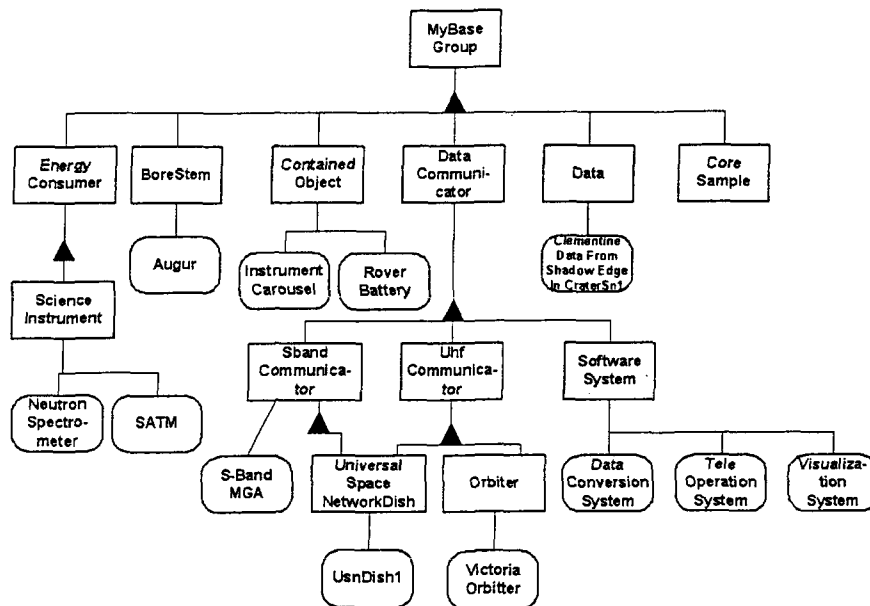


Figure 6. Victoria Object Model

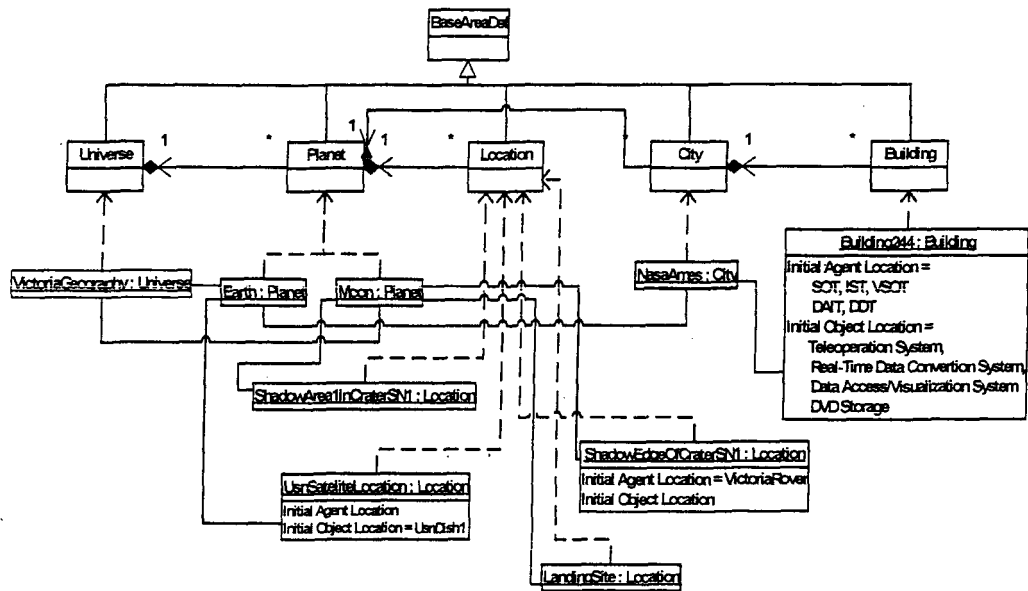


Figure 7. Victoria Geography Model

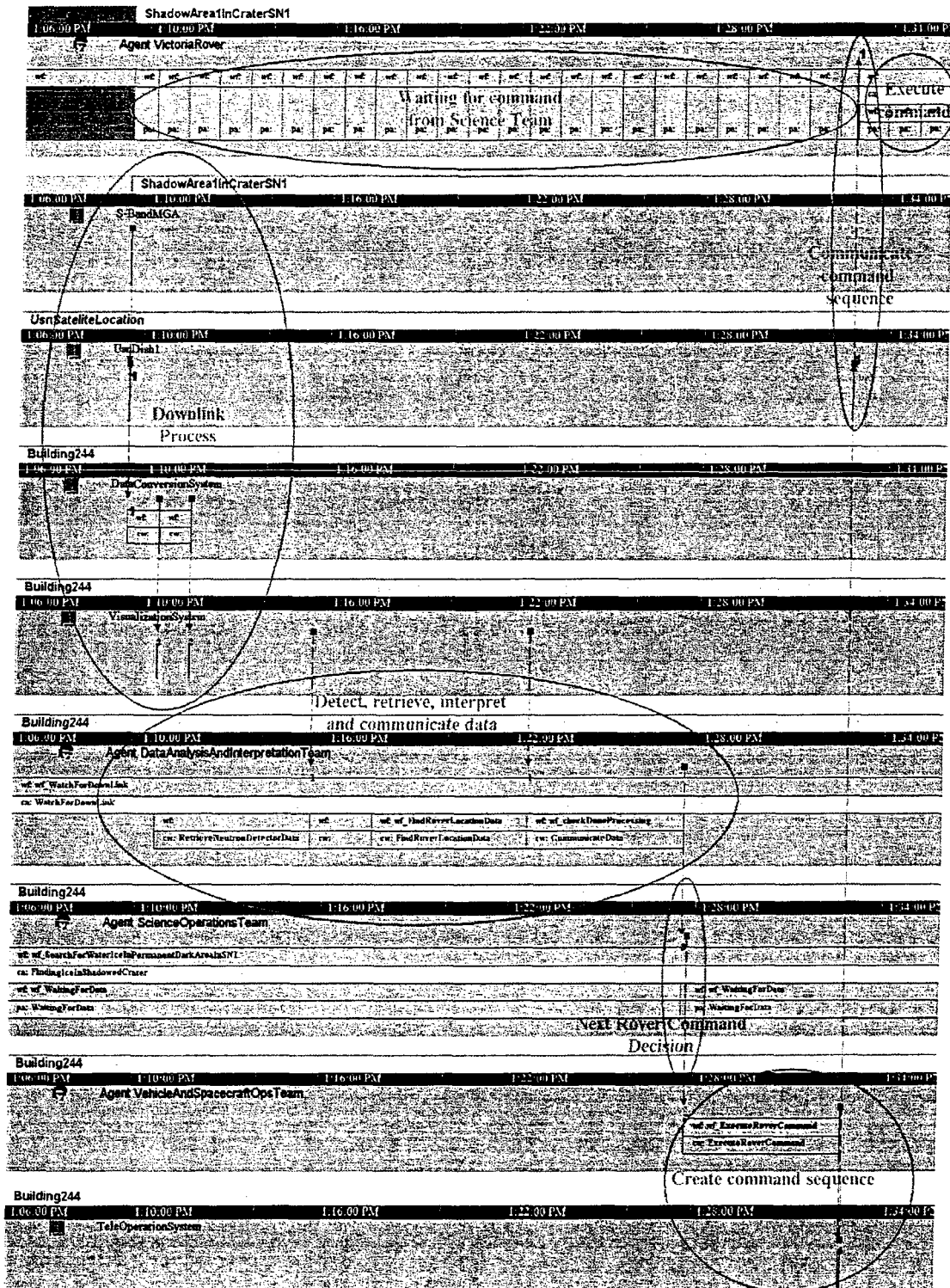


Figure 8. Simulation of downlink and second uplink command activities

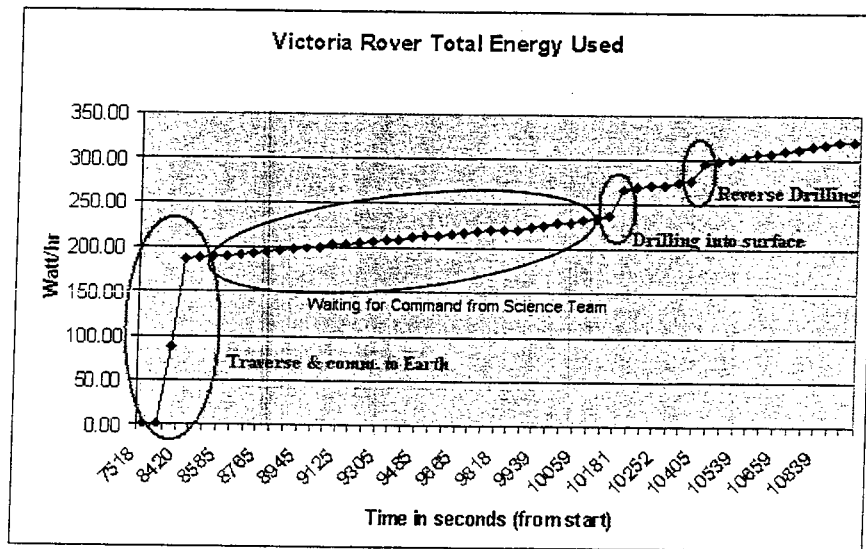


Figure 9. Energy consumption graphed from the simulation history database

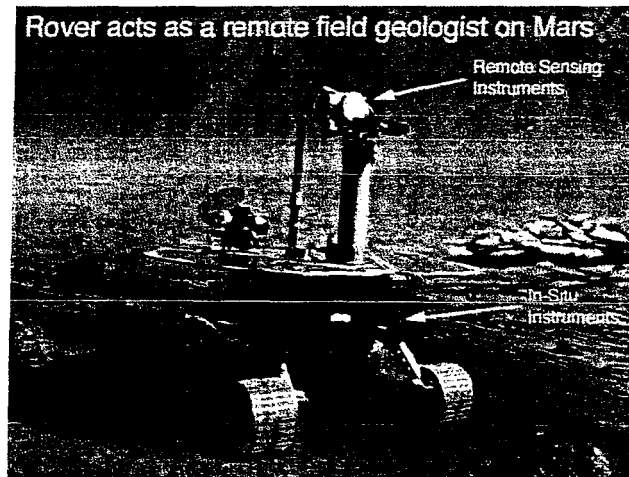


Figure 10. The MER mission's Athena rover showing remote sensing and in-situ instruments

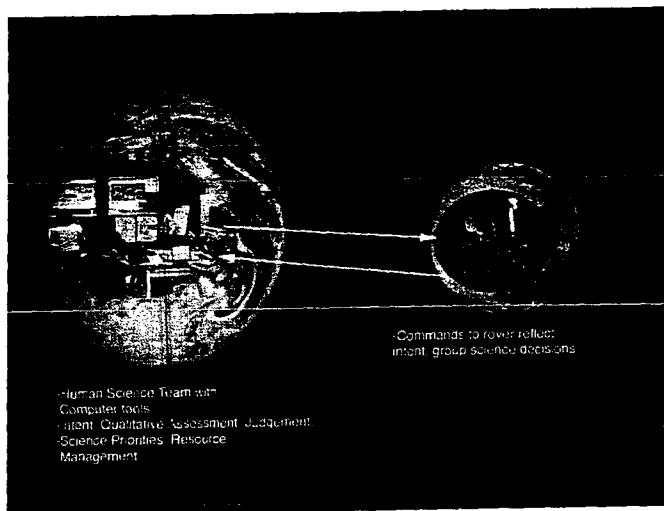


Figure 11. The science team on Earth receives data from the rovers and sends commands on a daily basis

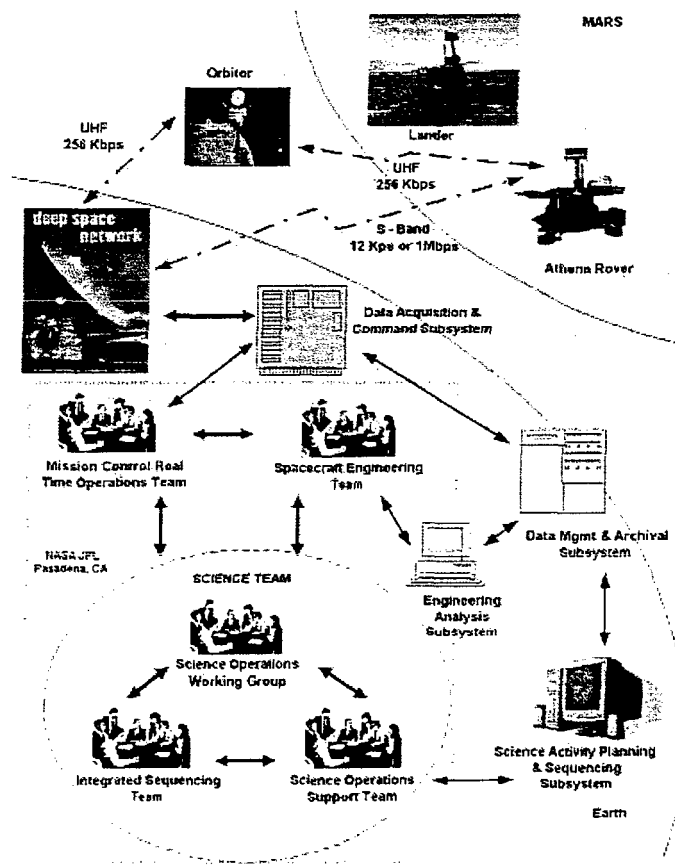


Figure 12. MER mission operations work system



Figure 13. MERBoard, a computer-based white board designed to facilitate science team collaborations during the MER mission.

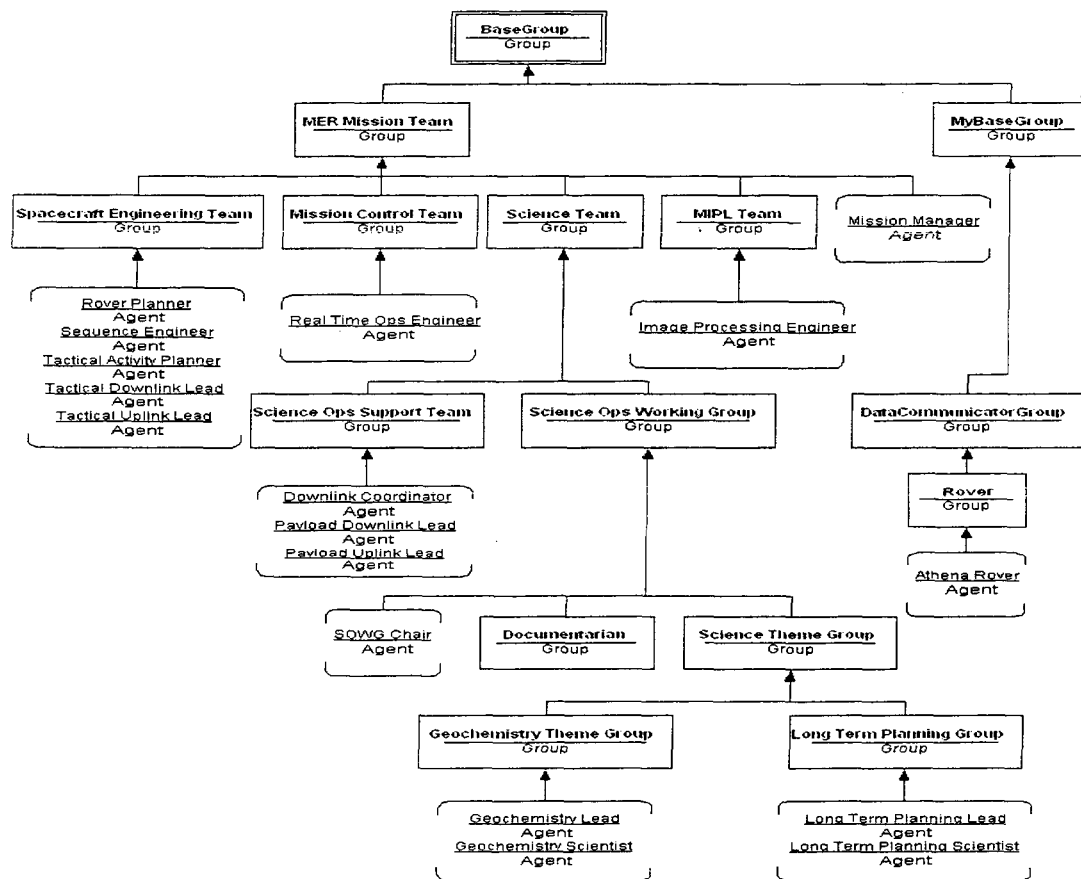


Figure 14. MER Agent Model

Table 2. Functional Activity Distribution over MER Mission Operations Team

	<i>Downlink Process</i>	<i>Uplink Process</i>
<i>MIPL Team</i>	<ul style="list-style-type: none"> • Collection of rover, image and payload/instrument data. • Enhancement of image data. 	
<i>Spacecraft Engineering Team</i>	<ul style="list-style-type: none"> • Analysis of rover data. • Identification of expected rover data not returned. 	<ul style="list-style-type: none"> • Build rover commands for science and rover maintenance. • Build rover commands for emergency or anomaly resolution.
<i>Science Ops Support Team</i>	<ul style="list-style-type: none"> • Enhancement of payload/instrument data. • Analysis of payload/instrument data. • Identification of payload/instrument expected data not returned. 	<ul style="list-style-type: none"> • Build payload/instrument commands for science or calibration. • Build payload/instrument commands for emergency or anomaly resolution.
<i>Geochemistry Theme Group</i>	<ul style="list-style-type: none"> • Scientific analysis of image and payload/instrument data. 	<ul style="list-style-type: none"> • Recommend both rover and payload/instrument commands for science experiments.
<i>Long Term Planning Theme Group</i>	<ul style="list-style-type: none"> • Scientific analysis of image and payload/instrument data. • Integrate returned data with long term scientific goals. 	<ul style="list-style-type: none"> • Recommend rover and payload/instrument commands to fulfill long-term scientific goals.
• Mission Control Team	<ul style="list-style-type: none"> • Telecommunications between Earth & Mars. 	<ul style="list-style-type: none"> • Telecommunications between Earth & Mars. • Radiation of commands to Rover.
• Rover	<ul style="list-style-type: none"> • Transmission of data. 	<ul style="list-style-type: none"> • Execution of commands

Table 3. MER and Victoria Agent Model Equivalence

Victoria Agent Model	MER Agent Model
Victoria Team	MER Mission Team
Instrument Synergy Team	Science Ops Support Team
Science Operations Team	Science Ops Working Group
Data Analysis and Interpretation Team	Spacecraft Engineering Team & Science Ops Support Team
Vehicle and Spacecraft Operations Team	Spacecraft Engineer Team & Mission Control Team
Data and Downlink Team	MIPL Team
Data Communicator	Data Communicator Group
Rover	Rover

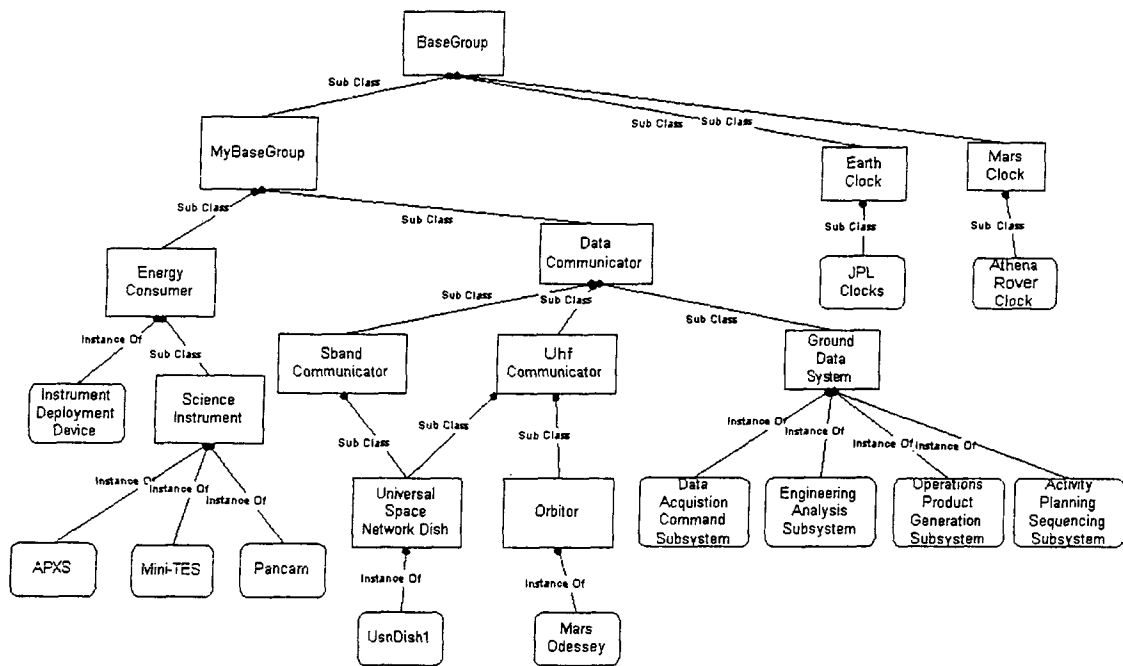


Figure 15. MER Physical Object Model

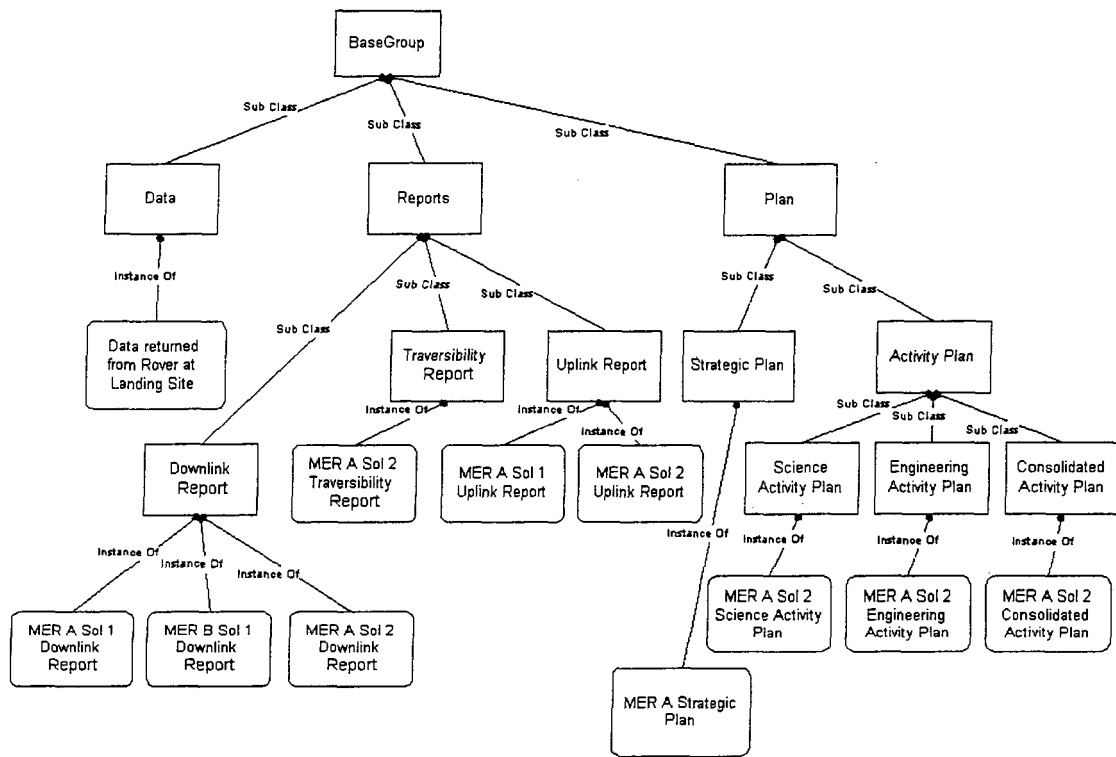


Figure 16. MER Data Object Model

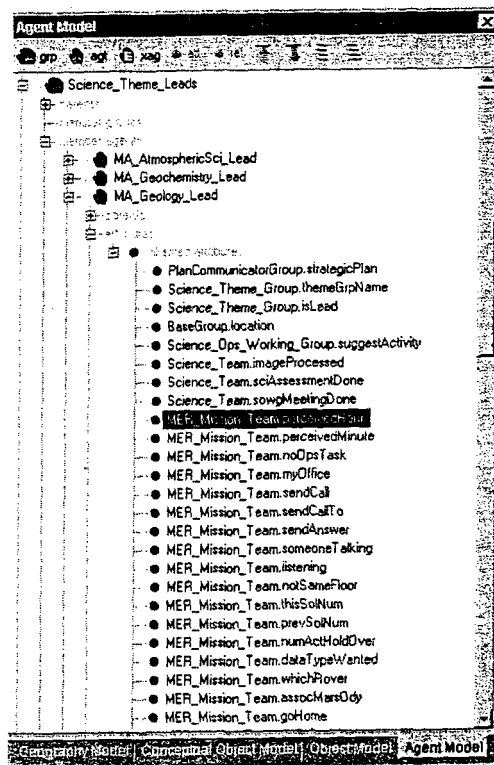


Figure 17. Group attributes

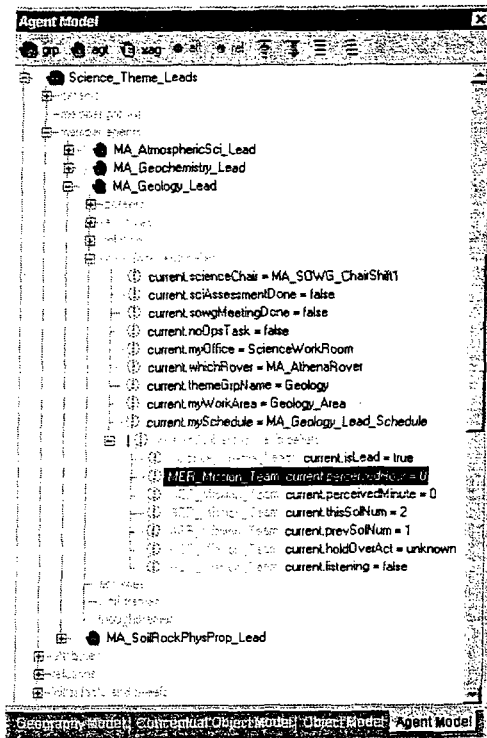


Figure 18. Group initial beliefs

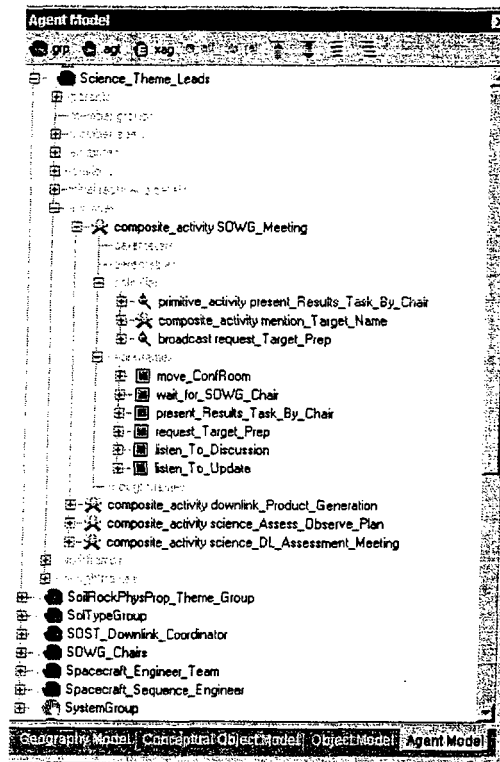


Figure 19. SOWG Meeting Activity

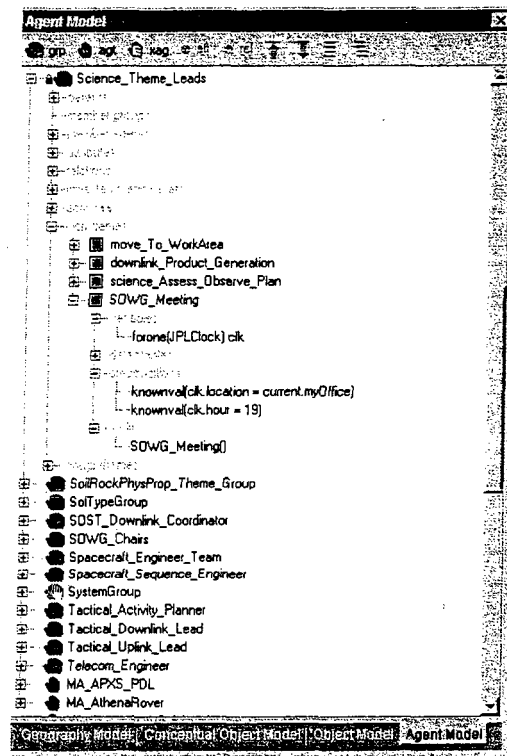


Figure 20. SOWG meeting workframe

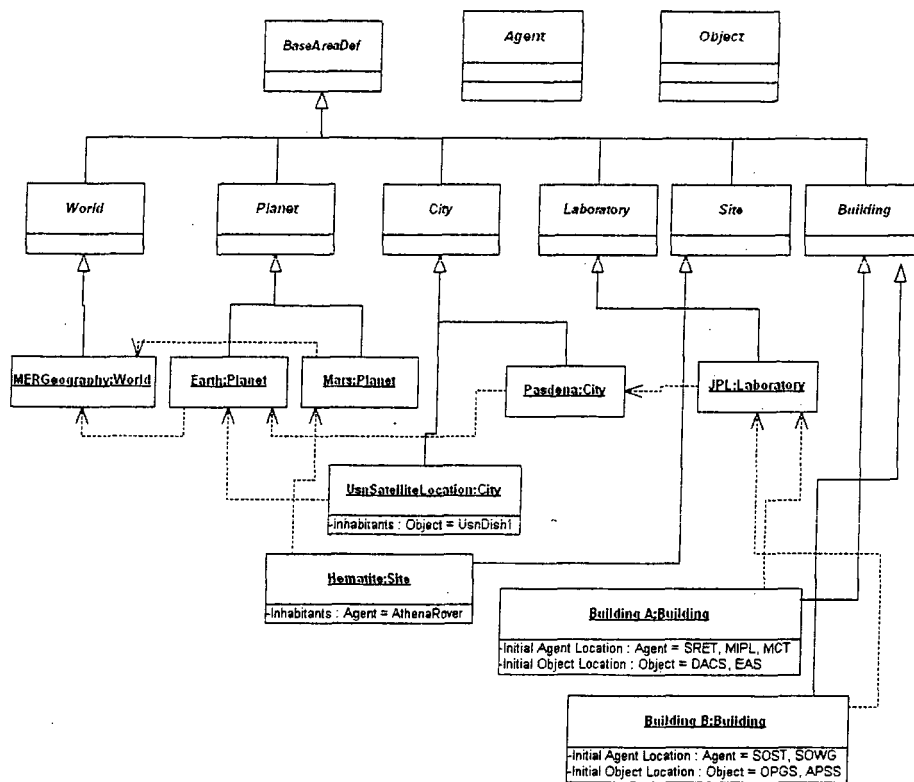


Figure 21. MER Geography Model

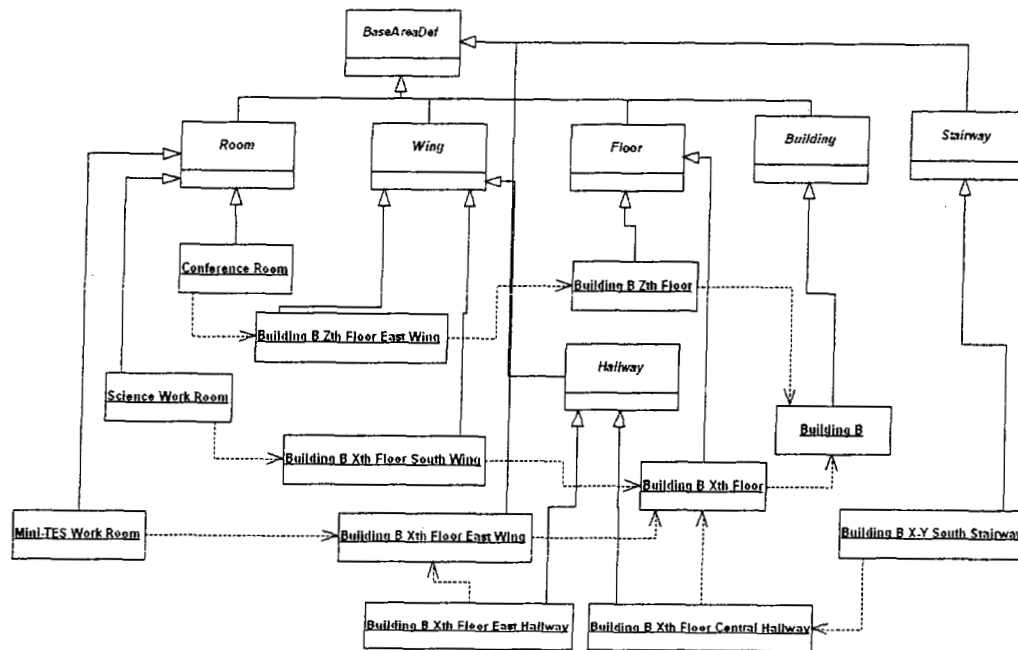


Figure 22. Building B's Geography Model

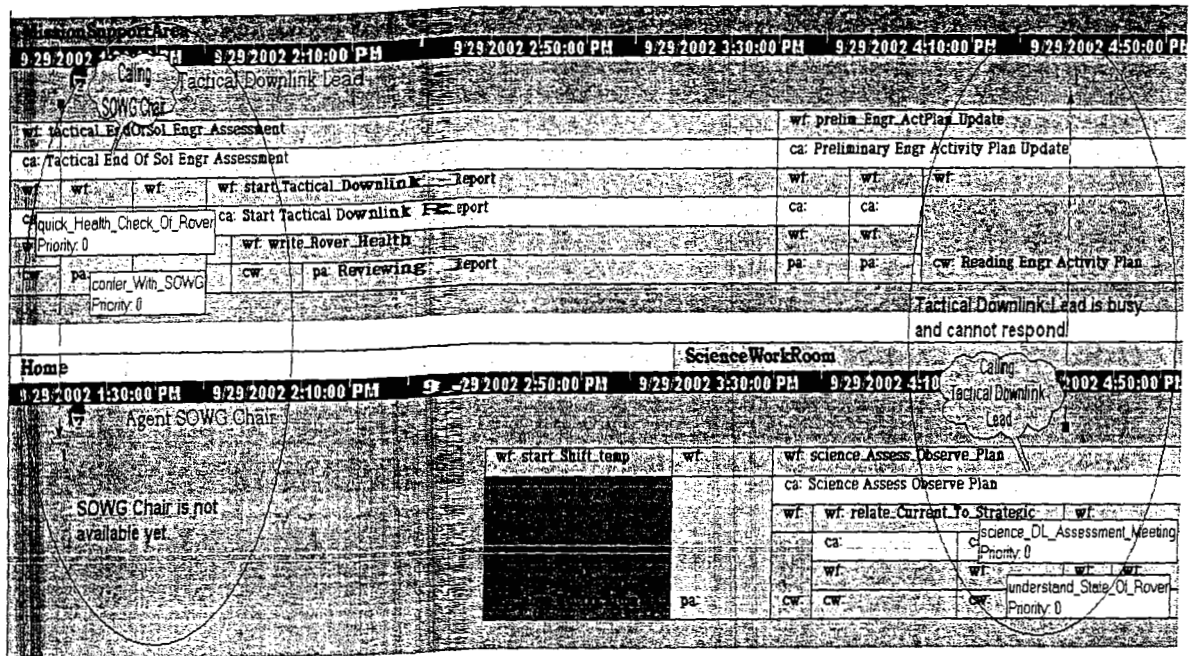


Figure 23 . Unsynchronized Communication Activities

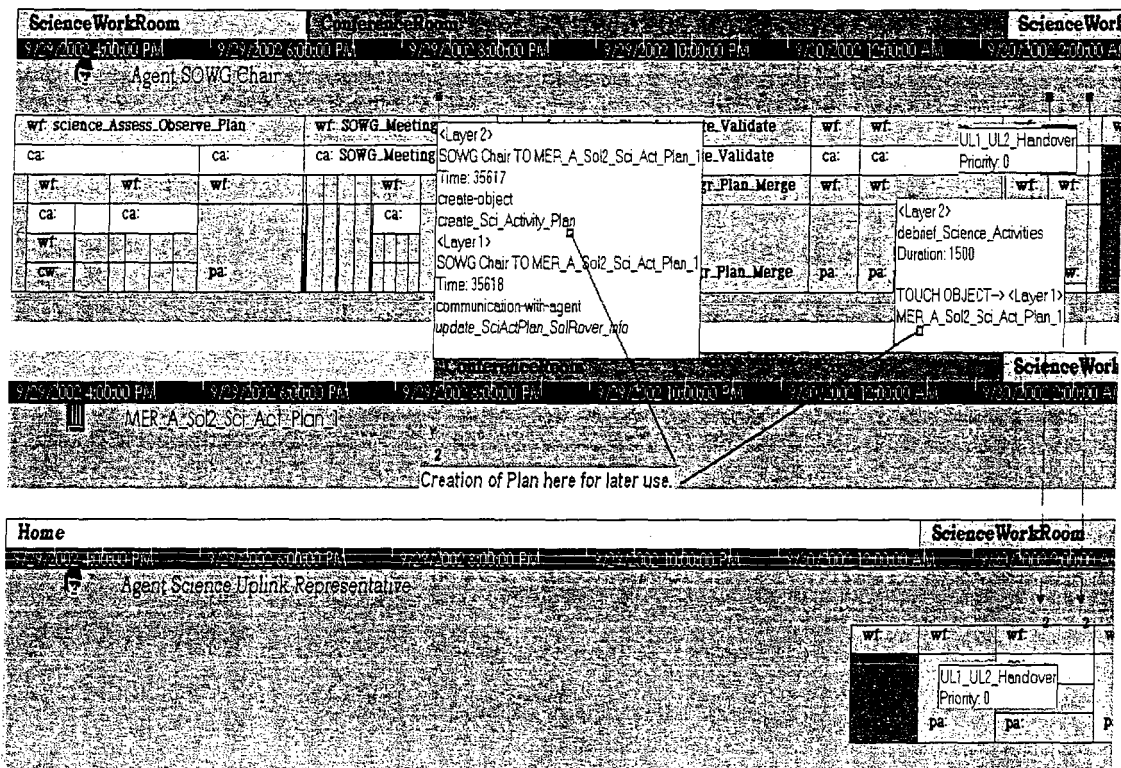


Figure 24. Handover of Information Activities

Scie Bldg	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z
9/29/2002 7:00:10 PM	9/29/2002 7:00:30 PM	9/29/2002 7:00:50 PM	9/29/2002 7:01:10 PM	9/29/2002 7:01:30 PM	9/29/2002 7:01:50 PM
Agent SOWG Chair					
wf: SOWG_Meeting					
ca: SOWG_Meeting					
wf: move_ConfRoom					
ca: Move_To_Area					
wf:	wf:	wf: Bldg_B_SouthStairwayY-Z_to_Bldg_B_SouthStairwayY-Z		wf:	wf:
wf: move_To_Location		Bldg_B_SouthStairwayY-Z_to_Bldg_B_2thFloor_CentralHallway Priority: 0			

Scie Bldg	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z
9/29/2002 7:00:10 PM	9/29/2002 7:00:30 PM	9/29/2002 7:00:50 PM	9/29/2002 7:01:10 PM	9/29/2002 7:01:30 PM	9/29/2002 7:01:50 PM
Agent Geochemistry Theme Group Lead					
wf: SOWG_Meeting					
ca: SOWG_Meeting					
wf: move_ConfRoom					
ca: Move_To_Area					
wf:	wf:	wf: Bldg_B_SouthStairwayY-Z_to_Bldg_B_SouthStairwayY-Z		wf: Bldg_B_SouthStairwayY-Z_to_Bldg_B_2thFloor_CentralHallway	
wf: move_To_Location		wf: move_To_Location		wf: move_To_Location	

Scie Bldg	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z	Bldg B South Stairway Y-Z
9/29/2002 7:00:10 PM	9/29/2002 7:00:30 PM	9/29/2002 7:00:50 PM	9/29/2002 7:01:10 PM	9/29/2002 7:01:30 PM	9/29/2002 7:01:50 PM
Agent Long Term Planning Theme Group Lead					
wf: SOWG_Meeting					
ca: SOWG_Meeting					
wf: move_ConfRoom					
ca: Move_To_Area					
wf:	wf:	wf: Bldg_B_SouthStairwayY-Z_to_Bldg_B_SouthStairwayY-Z		wf: Bldg_B_SouthStairwayY-Z_to_Bldg_B_2thFloor_CentralHallway	
wf: move_To_Location		wf: move_To_Location		wf: move_To_Location	

Figure 25. Simulation of Move Activities

<i>Position</i>	<i>Start Time</i>	<i>End Time</i>	<i>Tactical Timeline</i>	<i>Tasks</i>	<i>Process Steps</i>
Tactical Downlink Lead	10.30	13.00	Real Time Monitoring		
	10.30	10.35		roll_Call	Performing Roll Call
	10.35	11.22		access_prev_downlink_report	Access Previous Downlink Report
	10.35	10.35			Reading DL Report Sol Number
	10.35	10.35			Reading DL Report Sol Number
	10.35	10.55			Reading MER DL Report
	10.55	11.22			Reading MER DL Report
	11.22	13.00	Tactical End Of Sol Engr Assessment	direct_Real-Time_Monitoring	Direct Real-Time Monitoring
	13.00	16.00			
	13.00	13.00		launch_Engr_Analysis_SubSystem	open_EAS
	13.00	13.00			open_EAS
	13.00	13.20		access_MGS_Odyssey_Health_Readiness	access_Data_Via_Workstation
	13.00	13.05			send_Query
	13.05	13.05			look_For_Data
	13.05	13.20			read_Orbiter_Displayed_Data
	13.20	13.40		quick_Health_Check_Of_Rover	access_Data_Via_Workstation
	13.20	13.25			send_Query
	13.25	13.40			read_Rover_Displayed_Data
	13.25	13.25			look_For_Data
	13.40	13.40		confer_With_SOWG	Call SOWG Chair
	13.40	13.45		confer_With_SOWG	Wait SOWG Chair Answer
	13.45	13.45		confer_With_SOST	Call SOST Downlink Coordinator
	13.45	13.50		confer_With_SOST	Wait SDC Answer

Figure 26. MER Key Position Schedule for the Tactical Downlink Lead

1	10.35	11.00	SRET	Tactical Downlink Lead	Downlink Report = MER B Sol 1 DL Report	Reading MER DL Report	
2	11.00	11.27	SRET	Tactical Downlink Lead	Downlink Report = MER A Sol 1 DL Report	Reading MER DL Report	
3	13.05	13.20	SRET	Tactical Downlink Lead	Computer Workstation = MSA Eng Workstation	read_Orbiter_Displayed_Data	
4	13.25	13.40	SRET	Tactical Downlink Lead	Computer Workstation = MSA Eng Workstation	read_Rover_Displayed_Data	
5	13.50	13.55	SRET	Tactical Downlink Lead		Updating Sol Rover Info	Downlink Report = MER_A_Sol2_DL_Report_1
6	13.55	14.10	SRET	Tactical Downlink Lead		Writing Rover Health Info	Downlink Report = MER_A_Sol2_DL_Report_1
7	14.00	14.33	MPT	Mission Planner	Strategic Plan = MER A Strategic Plan	read_Strategic_Plan	
8	14.34	14.54	MPT	Mission Planner	Downlink Report = MER B Sol 1 DL Report	Reading MER DL Report	
9	14.54	15.12	MPT	Mission Planner	Downlink Report = MER A Sol 1 DL Report	Reading MER DL Report	
10	15.00	15.15	SRET	Tactical Activity Planner	Strategic Plan = MER A Strategic Plan	read_Strategic_Plan	
11	15.12	15.44	MPT	Mission Planner	Uplink Report = MER A Sol 1 UL Report	understand_MER_UL_Report	

Figure 27. MER Reporting Schedule

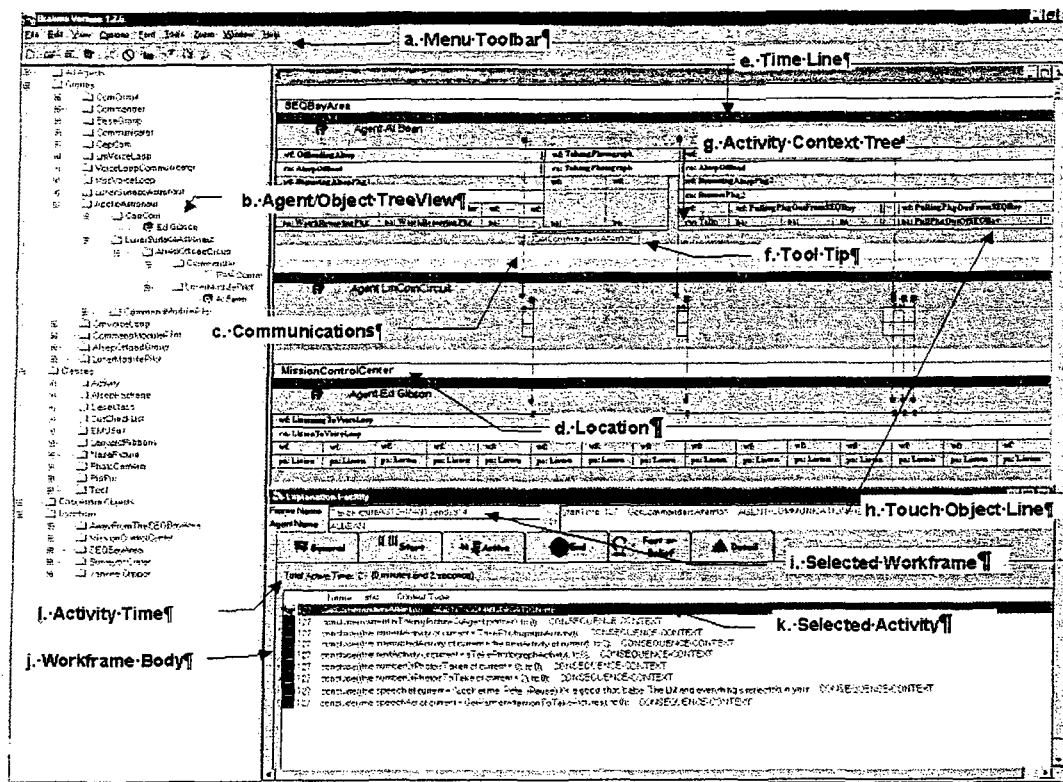


Figure 28. AgentViewer Explanation